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SUMMARY REPORT:
WORKSHOP ON VEHICLE RIDE QUALITY
WILLIAMSBURG, VIRGINIA, AUGUST 13-15, 1975

A. R. Kuhlthau
Anna M. Wichansky
(Editors)

U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

JULY 1977

FINAL REPORT

Prepared for

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16. Abstract

This report summarizes the proceedings of the 1975 Ride Quality Workshops, which were jointly sponsored by the U.S. Department of Transportation and the National Aeronautics and Space Administration and held in Williamsburg, Virginia during August 13-15, 1975. The workshops were conducted to review the information presented at the 1975 Ride Quality Symposium held during August 11-12, and to assess the state of the art in ride quality as surmised by various workshop participants. The proceedings are organized according to the main topics discussed by the four workshop groups: Accomplishments in Ride Quality Research, Needs of the Transportation Community, Ride Quality Research Techniques, and Ride and Environment Control Techniques. In addition, an appendix on scaling techniques and a list of workshop participants are included in the report.

17. Key Words
Ride Quality Workshops,
Transportation Community Needs,
Research Methodology, Scaling
Ride Control, Research Accomplishments

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PREFACE

In August of 1975, a joint symposium and workshop on vehicle ride quality, sponsored cooperatively by the U.S. Department of Transportation and by the National Aeronautics and Space Administration, was held in Williamsburg, Virginia.

The goal of the symposium was to provide an open forum for the presentation and discussion of latest contributions to the state-of-the-art—thus improving the technology base of ride quality information applicable to current and proposed transportation systems. Twenty-eight papers were selected for presentation by scientists and engineers from the United States and Great Britain. These papers have been published as a proceedings, and are available to the general public.*

The three-day workshop immediately following the symposium was conducted to review the information gained from the symposium, combine it with previous knowledge, and summarize the state-of-the-art as seen by the participants.

Four major discussion groups were formed,** with the members of each selected by the organizing committee. These groups were:

Group 1. Accomplishments in Ride Quality Research—Present and Near Future

Group 2. Needs of the Transportation Community—Present and Near Future

---

*Proceedings of the 1975 Ride Quality Symposium, NASA TM X-3295, DOT-TSC-OST-75-40, 1975.

**A list of the workshop participants is given in each section of this report and in summary form in Appendix II.

Group 3. Ride Quality Research Techniques

Group 4. Ride and Environment Control Techniques

Each group was free to establish its own format for its activities, with the chairmen and co-chairmen charged with the responsibility of preparing a summary of the group's activities. This volume therefore represents a compendium of these group reports. Editorial license has been used sparingly throughout the main body of the report. No attempt has been made to force the material into a common style, as this might detract from the value obtained through direct exposure to the enthusiasm and concerns of the participants.

However, we do take full credit (or blame) for inserting Appendix I, On Scaling Techniques. Our justification for this comes from the perception gained while editing the various sections that there is indeed a gap between the perspectives of the two main groups active in the ride quality field: those scientists and engineers involved in analysis and design, and those involved in human factors. We hope that this appendix, prepared with the help of several of the members of Group III, will be of some value in bridging this gap.

We wish to express our sincere appreciation to the chairmen and co-chairmen of the study groups. Their excellent work in preparing their reports has made our work both easy and enjoyable. We also wish to thank the Symposium and Workshop coordinators, John J. Fearnsides, (U.S. D.O.T./Office of

Secretary), Raymond P. Whitten (NASA/Headquarters), E. Donald Sussman(U.S. DOT/Transportation Systems Center), and Dr. William Conner (NASA/Langley Research Center), who initiated, planned, and secured support for these workshops, and whose efforts have made them such a success.

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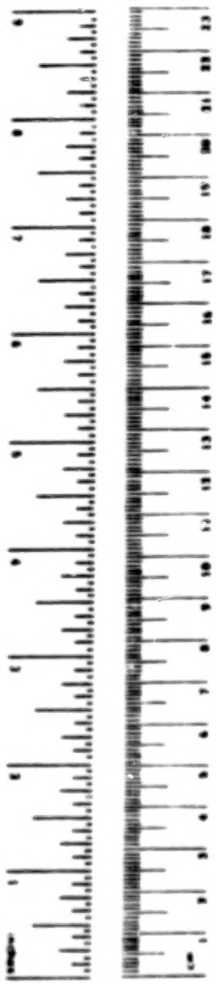
METRIC CONVERSION FACTORS

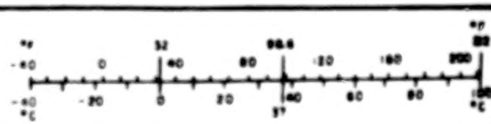
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find
	LENGTH		
mm	millimeters	0.04	inches
cm	centimeters	0.4	inches
m	meters	3.3	feet
m	meters	1.1	yards
km	kilometers	0.6	miles
	AREA		
cm^2	square centimeters	0.16	square inches
m^2	square meters	1.2	square yards
km^2	square kilometers	0.4	square miles
ha	hectares (10,000 m^2)	2.5	acres
	MASS (weight)		
g	grams	0.035	ounces
kg	kilograms	2.2	pounds
t	tonnes (1000 kg)	1.1	short tons
	VOLUME		
ml	milliliters	0.03	fluid ounces
l	liters	2.1	pints
l	liters	1.06	quarts
l	liters	0.26	gallons
m^3	cubic meters	35	cubic feet
m^3	cubic meters	1.3	cubic yards
	TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature



WORKING GROUP I - ACCOMPLISHMENTS IN RIDE QUALITY RESEARCH--
PRESENT AND NEAR FUTURE

PARTICIPANTS: Michael J. Griffin, Univ. of Southampton, UK
Ira D. Jacobson, Univ. of Virginia (Chairman)
Robert N. Janeway, Janeway Engineering Company
John P. Jankovich, Dept. of Transportation (Co-Chairman)
Paul M. Kenner, Vought Systems Division
Craig C. Smith, Univ. of Texas
David G. Stephens, NASA Langley Research Center
Henning E. Von Gierke, Biodynamics & Bionics Division, Aerospace Medical Research Laboratory
James C. Wambold, Pennsylvania State Univ.

INTRODUCTION

The objective of the activities of Working Group I was to critically review the accomplishments, the range, the completeness and shortcomings of results, as well as the future direction of investigations in the field of ride quality research. Areas of research in the field of ride quality were categorized into generic subdivisions. No attempt was made to evaluate specific investigators, but rather, to critically assess the applicability of the work done to date, in progress, or planned for the future. The following generic areas were identified:

Single degree of freedom simulations;
Multiple degrees of freedom simulations;
Field simulations;
Field experiments;
Surveys/reviews; and
Modeling techniques.

From this review a consensus was reached on the projection of needs for future research efforts, including a prioritization, as well as time and cost estimates of ride quality studies. It is encouraging to note that good agreement was found in the opinions of the Workshop participants, enabling

them to prepare a list of important studies which need to be accomplished in the near future. The Working Group found that future studies must be conducted in the following areas (not in order of importance):

- Low-frequency vibration effects (below 1 Hz);
- Detailed field experiments;
- Combined effects of noise and vibration;
- Rotational vibrations;
- Impulse and shock effects;
- Combining frequency and degrees of freedom studies;
- Development of systems model;
- Activity interference;
- Sustained acceleration;
- Time duration effects;
- Development of measurement techniques; and
- Development of a ride quality meter.

In discussing the accomplishments, needs and shortcomings of each of the above subdivisions of ride quality research, the Group attempted to focus its comments on the applicability of the information generated for developing (a) relative evaluation measures (yardsticks), (b) short/long haul system evaluation techniques, (c) areas where needs for ride quality specifications exist, and (d) design information for improvements. The main thrust of emphasis was placed almost entirely on the ride quality problems of the passenger and not on those of the operator; although it was recognized that in some vehicle systems the ride environment of the operator could be equally important. Similarly, the questions of performance, tolerance, and occupational health were omitted from discussion. This fact by no means implies that they are less important; they were not discussed solely because they were outside the charge of the Working Group and time would not allow their inclusion.

CONCLUSIONS OF THE WORKING GROUP

The different types of research studies were found, in general, to complement one another. It was felt that the field studies, among the subdivisions listed above, provide the most realistic ride environment, while single-axis simulators provide the least. Assessment of controllability of input stimuli for these two groups of experiments would reverse their order: single-axis simulators being the most controllable and field studies the least. This finding is depicted in Fig. 1. A comprehensive list of the accomplishments, needs, results and shortcomings for each of the experimental areas as well as for survey and review works as established by the participants is presented in Tables IA through IE. These tables are self-explanatory. However, some special comments not reflected in the Tables are presented in the next section.

In summary, it was concluded that at the present time a basic understanding of the complex problem of ride quality has been achieved to a degree which enables the specialist to have some preliminary insight into and to define the direction of future activities, and perhaps even to see the light at the end of the tunnel.

DISCUSSION

One item of special concern to the experimenters in the U.S. is the growing legal implications of using human subjects in experiments. Difficulties arise, first from the obvious liability incurred by the experimenter, and secondly, and perhaps more importantly, from the restrictions imposed on the subject population by legislative regulation. This has special implications in ride quality research where data for individuals on the tail of the distribution curve and not necessarily the "norm" are of interest. These individuals

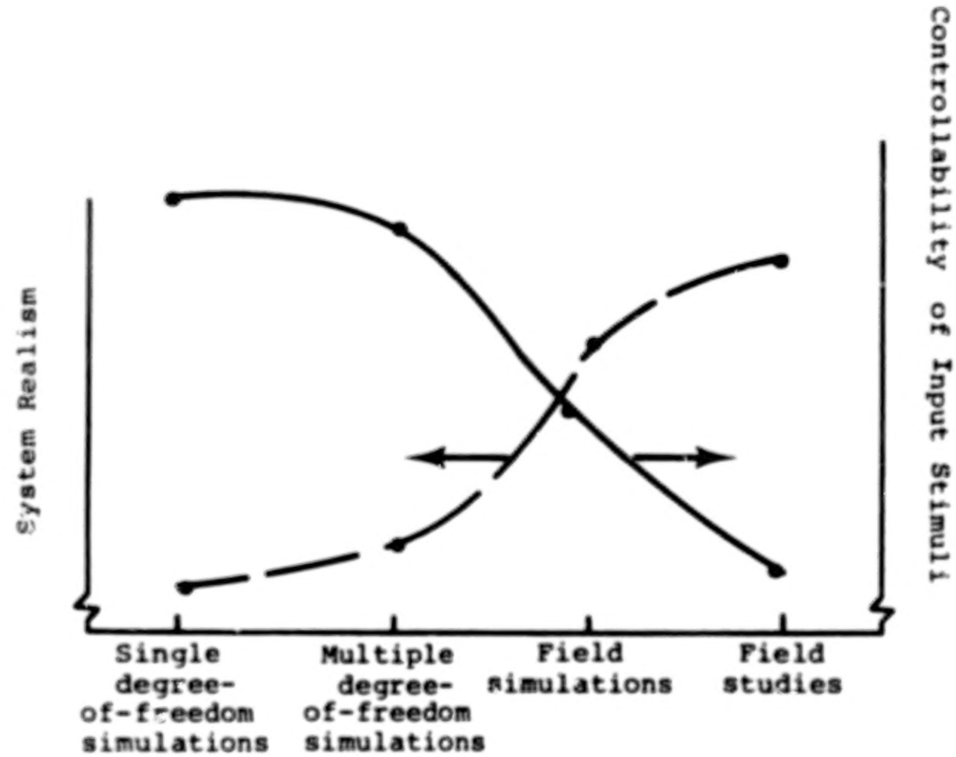


Figure 1. Relationship of system realism to controllability of input stimuli in the various areas of ride quality investigations.

Tables I.a - I.e

	Accomp.	Needs (additive)	Pros	Cons
I-Degree of Freedom Simulations I.a	freq. (1-20Hz) effects on man-relatively well known for vert. & horiz. directions (i.e. relative effects) indications exist that extrapolation is possible beginning to understand interference/masking effects of varying frequencies	-angular data -low freq. data (.1-2Hz) -sustained accel. -jerk -long-term studies -varying env. -duration -activity interference -horizontal data -summation technique -multiple f's -discrete inputs -pure tones -define input -justify extension to random stimulus -include other env. stimuli, e.g. noise, temp., etc.	-low cost -simplicity of eqpt. -control of environment -modelling is relatively simple	-least realistic -too much duplication -legal implication of using subjects -limited low freq. capability -restriction on population
Multiple D Simulations I.b	-test eqp't developed -info. on tolerance and perf. available -prelim. results (only) available -limited comfort studies available	-combined axis data -study complex multi-axis input -low freq. capability -determine fidelity requirements -all of the above	-adapt to any subset of axes -more realistic motion env. for most applic.	-complexity -high cost -lack of system realism -legal implication for using S's -restriction on population
Field Simulations e.g. test track, controlled env., controlled dynam. I.c	-spec. vehicles tested and evaluated -indications that sim. data can be applied to field -some info. on occup./handling effects -endurance info. -define environments	-info. on pass reaction -info. to validate/find relationships between sim & field studies -occup./handling effects -complex envir. factors effects -simulate future/concept. systems	-more realistic than lab sim -psycho. variables -environ. -hardware test possible -demonstration capability -validation capability -standard for vehicle test -def'n of surface or guideway -operator in loop	-lack of control -response limits -high cost -application limited

Tables I.a - I.e cont.

Field Experiments e.g. Fare paying, Captive, Operator I.d	-knowledge of populations for existing modes -environmental measures available for existing systems -subjective data available (prelim.) -situation specific models developed -effects of population stratification determined -relative importance of environ factors and utility variables -same time effect data available	-sleep requirements -data for determining sim environ. needed -rel. importance of utility factors -short vs. long term data -more complete measures (noise, 6DOF, temp,...) -establish commonality & uniqueness -coordinate data w/subj. measures for correl. analysis -info on activities desired -info. on activity interference -cross correlate modes -analysis of composite environ. -continuing info to estab. attitude changes	-max. realism -not a "human exp.", no legal probs. -psych/social factors incl. -validate applicability of lab results -screening studies for perspective -chronic studies -attitudinal changes	-need large # of S's -lack of control -difficult to isolate effects -range limited -predictions difficult
Surveys/Reviews I.e	-stimulated research -standards available -info. exchange -covers areas not in standards	-more data availability -coord.of info. Natl Group -cooperative research -further work on recommended practices -simplify measuring criteria -requires update -individual differences incorporated	-info. exchanges -can write specs. -judging of new situations -saves money & time -stimulates directed research	-legal consid.

may well be the young, old, infirm, pregnant, or other special groups of subjects generally affected by regulation for inclusion in simulator experiments.

Some discussion was centered on the need for "system" realism. What may be acceptable in one transportation context, may not be acceptable in another. The effects of experience, expectations, motivation, and a host of other social/psychological variables are not well understood. The total system must ultimately be analyzed with ride quality as one important part of the total problem.

Definition of inputs still requires further work. Clear input definition is important in two respects. First, ride quality information can be used in modeling only if the input stimuli are quantified in sufficient detail. Secondly, the location of the input to the human, i.e., feet, torso, buttocks, head, etc., may influence the perception of ride quality. Activity interference was another important area of consideration. Activities vary, depending on the mode, type, and length of the trip. They range from sleeping to reading and include eating, drinking, talking, looking out windows, etc.

Some discussion was centered on modeling of ride comfort and on the availability of guidelines. No consensus was reached on the best or preferred approaches to the problem of modeling techniques, since it was felt that these efforts were in an early stage of development. Similarly, although some limitations were noted, the guidelines in existence were neither endorsed nor eliminated as being in error. The guidelines presently available fall short of being all-inclusive. The most apparent inadequacies arise from the inability of the various guidelines to combine simultaneous inputs along different axes, and to predict time duration effects. Table 2 presents a list of guidelines which are identified by the

participants as basic documents. Table 2 also indicates the instrumentation methodology and the limitations of the various guidelines. The measures used in instrumentation of ride quality research were classified as:

(a) rms acceleration, unweighted;
(b) rms, weighted;
(c) rms, in bands;
(d) peak level;
(e) power spectral density;
(f) amplitude-frequency density;
(g) exceedance values; and
(h) histogram.

Table 2

Summary of Existing Guidelines

Guideline	Type of Measures*	Limitations**
(1) ISO	(b),(c)	rest factor < 3, freq. > 1 Hz
(2) Pradko-Lee	(b)	freq. > 1 Hz
(3) Janeway	(b)	"
(4) Coermann	(b)	"
(5) UTACV	(e)	
(6) SAE	(b),(c)	Agricultural Equipment
(7) MIL Standard	(c)	freq. > 1 Hz
(8) AF		Performance Rating

*(a), (b), etc. refer to measures identified on page 8.

**All guidelines suffer from inability to predict effects of axes combinations and duration.

(1),(2),etc. refer to references given on page 10.

References to Guidelines in Table 2

(1) "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," International Standard ISO 2631-1974.

(2) Pradko, F., and R. A. Lee, "Vibration Comfort Criteria," SAE Paper 660139 (1966).

(3) Janeway, R. N., "Vibration Limits to Fit the Passengers," SAE Journal, August 1948, pp. 48-49.

(4) Coermann, Rolf R., "The Mechanical Impedance of the Human Body in Sitting and Standing Position at Low Frequencies," Human Factors, Vol. 4, No. 5, pp. 227-253, October 1962.

(5) "Performance Specification and Engineering Requirements for Urban Tracked Air Cushion Vehicle," DOT-UT-10026, May 10, 1971.

(6) "Measurement of Whole-Body Vibration of the Seated Operator of Agricultural Equipment," SAE Recommended Practice, SAE J1013.

(7) Military Standard "Human Engineering Design Criteria for Military Systems, Equipment and Facilities," MIL-STD-1472B, December 1974.

(8) Military Specification, "Flight Control Systems-Design, Installation & Test of Piloted Aircraft," General Specification for MIL-F-9490D (USAF), 6 June 1975.

SPECIFIC COMMENTS ON FUTURE INVESTIGATIONS

Each participant was asked to comment on those areas of ride quality problems where in his own opinion there was a need for future investigation. Table 3 indicates the consensus of the group with estimates of the time, cost, and type of the investigation (i.e., laboratory, field experiments) which should be undertaken in order to achieve a first generation understanding.

In addition to the consensus of the Working Group on ride-related information needs (Table 3), specific recommendations of the individual participants were solicited. The specific recommendations were easily categorized into a number of topics. The topics and the opinions of the individuals (without personal indentification) are presented below:

Low Frequency Vibration

"Work needs to be done at low frequency, i.e., below 1 or 2 Hz. This is not of major concern for cars. The work should be done in field simulators first and later in laboratory simulators."

"Motion sickness effects deserve a high priority. The studies should aim at producing a procedure for predicting the percentage of subjects in several common groups who will become sick due to low frequency motion. The motions to be investigated must include movements in all six axes in isolation and in combination."

"Conduct simulated studies to extend "equal comfort" to 0.1 Hz [in ISO 2631]."

Table 3

PRIORITIES FOR THE NEAR FUTURE
(in approximate order of importance)

Low frequency vibration	laboratory	3 yrs.	$300,000
Detailed field studies (incl. complete environment)	field	5 yrs.	$500,000
Combining frequencies and degrees-of-freedom	laboratory	2 yrs.	$200,000
Examine importance of noise	laboratory & field	2 yrs.	$200,000
Effects of impulses	laboratory & field	3 yrs.	$300,000
Time duration effects	laboratory & field	3 yrs.	
Sustained acceleration effects	laboratory & field	1 yr.	$100,000
Rotational degees of freedom	laboratory & field	3 yrs.	$300,000
Develop systems model	field	5 yrs.	$200,000
Develop measurement technique		2 yrs.	$200,000
Develop meter		2 yrs.	$150,000

"Low frequency response [of the traveling population] between 0.05-1 Hz in the vertical, lateral directions [...is] needed for the specification, design, and acceptance of all modes of transportation systems."

Detailed Field Studies

"Field tests [are needed] to verify/define applicability of existing criteria within various vehicle groups."

"Develop relationships between vibrations and other psychological factors, [their] relative importance, etc."

"Determination of relative importance of ride quality in passenger acceptance of the transportation system (sociological and systems approach), [in the form of] guidelines [should be developed] for the transportation system designer and user (municipalities, cities, transportation authorities) on how refined a ride is needed under their individual socioeconomic, operational condition. Purpose is to avoid overspecification as far as ride quality is concerned."

"Evaluate a representative cross-section of all rides of concern (surface, air, sea) with the same methodology (six degress of freedom, ISO). Document vibration environments with ISO weighting function including tentative 0.1-1 Hz weighting. Document other environmental factors (noise sustained, seating, space, etc.). Observe, measure, question activity, interference, desirable activity. Establish activity interference criteria and comfort."

"Conduct longitudinal studies in public adaptability to new ride environments. These must be field studies [designed] with the transition to new transpor-

tation systems, introduction of new aircraft (low level but continuing efforts, using constant methodology)."

Combination of Frequency Inputs and Degrees of Freedom

"Another effect that needs to be studied is coupling of degrees of freedom and how they should be added. This is of less importance to ground vehicles, such as cars, than it is for air and water vehicles. This work will need to be done in multi-degree-of-freedom simulators."

"Determine coupling between various axes of degrees of freedom (simulators first/field studies later)."

"[Develop] combined axes vibration methodology for combining energy, power, etc. of vibration which is found in each axis...Laboratory tests in vertical and lateral [directions are needed]."

"Combined frequency vibration (single axis) [studies should] examine the concept of masking vs. weighted rms, etc."

"Tests with multiple inputs, both subjective and objective measurements (absorbed power) [are needed]:

1. Same frequencies, different directions,
2. Different frequencies, same direction, and
3. Different frequencies, different directions."

Role and Importance of Noise

"Begin to evaluate the effects of known vibrational environmental factors on ride comfort, especially the coupled effects. How do the vibrational limits change with noise added, with temperature, etc.? This work will [have to be] done in simulators, in particular, one degree of freedom [simulator] to start with."

"Methodology [is needed] for studying and understanding interior noise and how it combines with vibration. [It] must include safety, performance, and hearing [effects]."

"Determine the importance of adding noise to vibration environment. Up to what levels does noise not interfere with vibration? In other words, [establish] relative weighting of noise interference vs. vibration interference."

"Noise can be either synergistic or antagonistic in other applications. Its effect in conjunction with vibration should be determined at an early date so as to help in designing future simulator studies."

Shock Effects

"[Use] best present methods or establish new ones as required to allow for single inputs such as an air pocket, large bump, etc. and along with this study effects of past history. Thus, do a few large shocks lower the limits for the next half-hour, next hour, etc?"

"There is a current need to determine the importance of occasional impacts that produce a high crest-factor motion."

"Clarify the role of jerk in sustained accelerations ...to improve capacity of ground transportation systems by permitting high acceleration and deceleration levels, but not hindering ride quality or ride acceptance."

"Study [the] effects of transient accelerations (short, sustained) and high-crest factors, short term acceptance/discomfort response as well as effect on overall long-term, integrated ride evaluation (linear degress of freedom)."

Time Duration Effects

"How cumulative are time effects? Does a ride near a given limit become unacceptable with time? It appears that, in some frequency ranges, time lowers comfort levels and in some ranges it raises them. That is, in some frequency ranges, people adapt and in others they get worse again. This work should be started in field studies and later brought into laboratory simulators."

"Determine exposure time effects (more precisely than exist in ISO [2631])."

"Develop "single event" measures and long-term measures as a function of time."

Sustained Acceleration Effects

"Passengers' response to sustained dynamic environment: acceleration, deceleration [must be studied.] Data should be represented as percentages of comfort rating, e.g., 50%, 75%, 90% of the subjects found it acceptable, comfortable, etc. The answers should be explored in both laboratory simulator and field studies."

Rotational Degrees of Freedom

"There is a need for further work on angular motions and angular motion combined with linear."

"Generate "equal comfort" curves for three angular degrees of freedom."

"Angular acceleration [studies] in roll and pitch [and yaw] to determine critical frequency range, critical acceleration range [are] needed for the specification, design, and acceptance of all modes."

"Study discomfort/interference limits for rotational degrees of freedom, particularly for prolonged, repeated exposures (0.1 to 10 Hz first)."

"[Data are needed on] angular modes (roll and pitch) with subject confined in seat."

Development of a System Model

"Work needs to be started to compare different models, to evaluate their effectiveness in building and testing transportation systems. I see that as a first cut models that work for a system need to be found for the various transportation modes."

"Psycho-sociological studies should be [conducted] to determine the relative importance of ride quality in passenger acceptance of one mode of transportation over another; i.e., the passenger utility function of ride quality in public acceptance must be established."

"A system model would enable designers to trade off between ride quality factors (vibration, noise, etc.) and system variables (cost, time cost, etc.). Without this, one may under- or over-design for ride quality which will become apparent only when some system parameter changes."

Development of Measurement Techniques

"Development of measuring techniques which could be applied fairly universally to describe physical variables of research and field studies [is needed]. Specifications of the measurement technique [should] be included in a national standard-type document."

"Reducing* methods need to be established so that works A and B have some common ground for comparison. This work needs to be done by a committee."

"Develop specifications (with alternatives) to ensure meaningful data reduction and interpretation, in ride evaluation."

---

*i.e., data reduction.

Development of a Ride Meter

"Develop and test standard ride quality meter based on ISO, including low-frequency extension (include pick-up plate)."

"Validation in the field of a model (meter) which accounts for vibration in all axes, noise and other important physical and subjective variables, and predicts comfort [needs to be done]."

Miscellaneous Comments

"People who earn their living by research are not the best people to define what areas they should next investigate. They have an informed opinion, but it can be somewhat biased. I think that research in this area should be heavily biased towards the needs of the "users" and I have not attempted to dictate their needs in this list of priorities."

"Examine the effects of vibration on reading, walking, sleeping, etc."

"Establish validity of transferring results which were obtained with experimental subjects to the response of one or another segment of the traveling public."

"Some method of weighting and combining response to obtain a measure of performance (single number) is essential in the (rational) vehicle/guideway design process."

"[Concerning] ride comfort of standing passengers, little or no experimental data are available; vibration specifications are needed; sustained acceleration, deceleration, and lateral levels should be specified."

"What the most suitable formats are for expressing passenger ride quality requirements should be explored:

rms, peak, power spectra; comfort index, ISO-type curves; 10%-50%-90% passenger acceptance curves."

"Development of a transfer function is needed to convert the ratings obtained from test subjects/selected sample into total population acceptance percentiles, e.g., it would be ideal if we could just test a group of 20 [people] and convert their ratings viably to how the general population (or one particular type of the traveling public) would rate the same [inputs]."

"Establish advisory board for advice and coordination in research plans (include all Government agencies with interest in results or capabilities/facilities). Use board for coordination of specifications for systems."

"Participate (NASA, DOT) and encourage (universities, industry) participation in ISO standardization activity. Provide funding for proper U. S. delegation to meetings. Submit national proposals for consideration by ISO."

Summary

Members of the Working Group were in agreement concerning the achievements and the possible future direction of ride quality research efforts. It was concluded that much work must still be accomplished, but answers to the most pressing problems are all within reach. There was general agreement on goals and objectives and it was found evident that a concerted effort could establish the basis for revealing the interrelationships in the entire problem area of ride quality and ride comfort in the near future.

WORKING GROUP II - NEEDS OF THE TRANSPORTATION COMMUNITY--PRESENT AND NEAR FUTURE

PARTICIPANTS:
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- Stanley Brumaghim, Boeing/Wichita
- Frank Condos, TRW
- D. William Conner, NASA Langley Research Center (Chairman)
- Boyd Cryer, General Motors Truck and Coach Div.
- John J. Fearnsides, US DOT/Office of Secretary
- Stanley E. Hindman, US DOT/Urban Mass Transportation Administration
- K. H. McGhee, Virginia Highway and Transportation Research Council
- George Onega, Bell Aerospace Corporation
- Robin K. Ransone, University of Virginia
- Richard L. Scharr, US DOT/Federal Railroad Administration (Co-Chairman)
- Paul R. Spencer, US DOT/Urban Mass Transportation Administration
- Allan Stave, Sikorsky Aircraft
- Avril Brenig, Acoustical Society of America

INTRODUCTION

Travelers' choice and use of transportation systems can be significantly influenced by ride quality. As used herein, ride quality is defined as the impact on the passenger of all aspects of the carrier vehicle physical environment that affect his acceptance of the ride. While motion and vibration are recognized as prime factors affecting subjective reactions, ride quality includes other factors as well (e.g., noise, roominess, etc.) which also can be important. Numerous studies of ride quality factors have been carried out over the years but unfortunately the cumulative information available oftentimes has proven inadequate for meaningful application. This situation exists partly because of the many variables (both subjective and objective) involved and of the interacting effects between variables. In addition, many of the technology generation efforts have been structured and carried out by research organizations more interested in

studying ride quality phenomena than in satisfying the particular needs of users. There has been a persistent lack of standardization in definition and measurement of the ride environment, in research methodologies and in the subjective rating scales used.

User groups embrace those that specify, design, analyze, procure, develop, operate and/or maintain transportation systems and include government, academic and industrial organizations. No prior effort has collectively addressed the technology needs of this wide a range of interest groups.

The central problem addressed in this section of the ride quality workshop was identification of present and future technology needs of government, academic, and industrial organizations concerned with transportation. The scope included needs associated with present, prototype and anticipated (spanning the next five years) vehicle systems for the transportation of people by air, water or land, and including interfacing system components (e.g., guideways) as well as the primary vehicles.

The approach followed in the workshop activity was review by a group, collectively knowledgeable in the appropriate transportation modes, of issues deemed pertinent to the central problem. The issues included:

Importance of ride quality;
Necessary technology;
Ride quality criteria;
Priority and timetable of needs;
The meeting of the needs.

To bring into focus individual interests and thinking at the outset, group members were polled in advance on specific issues. Group participation during the 2-1/2 day workshop included full-time attendance by eleven members and part-time attendance by four members.

PERCEIVED IMPORTANCE OF RIDE QUALITY

The significance of ride quality as a factor in the transportation of people is poorly understood in quantitative terms, particularly for situations where the quality of the ride tends to be marginal. Hence, the absolute importance of ride quality cannot yet be established, and perceived importance must suffice. To provide a qualitative assessment of perceived importance, the opinions of workshop group members were obtained on the following question:

> "How do you weigh vehicle ride quality as a factor in determining traveler acceptance and use (as opposed to other factors such as convenience of schedule, fares, etc.) of your mode of transportation and of competing modes of transportation for the same travel market?"

Table I summarizes the opinions expressed.

Table I

Mode	Importance of Ride Quality
Air (CTOL, STOL, Helicopter)	Behind Cost, Convenience and Performance
Highway (Urban/Intercity Bus)	Behind Schedule, Convenience, Reliability and Security
Automated Guideway Transit*	Behind Schedule, Triptime, Reliability and Cost
Marine (Hydrofoil, Hovercraft)	Ahead of Fare, Cost
Urban Rail	Behind Security and Reliability
Intercity Rail	Behind Cost, Convenience and Performance

*Automated Guideway Transit (AGT) ranges from Personal Rapid Transit (2-6 passengers, 0.5-3 seconds headway, no operator), through Group Rapid Transit (12-70 passengers, 3-90 seconds headway, no operator), to and including Rapid Rail (70-270 passengers, 90-180 seconds headway, with operator).

In answering the above question, group members interpreted the term "ride quality" to mean "perceived ride quality" or "expected ride quality" rather than "actual ride quality." The perceived importance was judged to be essentially the same for air and ground modes of transportation. Surveys of short-haul ground transportation indicated that while improvement was needed in vibration and motion, passengers did not consider it to be worth even an additional five cents per ride. For air and ground modes in general, the likelihood was considered low for mass rejection of existing vehicle systems because of inferior ride quality. The situation was quite different, however, for marine vehicles where oftentimes (e.g., between islands in Hawaii) passengers are willing to pay up to 50 percent more in fare cost to insure that the marine vehicle ride will be acceptable.

Ride quality was generally regarded by workshop members as a factor which requires a certain degree of attention to avoid a possible source of customer rejection. Concern in this area was expressed for several of the advanced vehicle systems now in design or under serious consideration. A general thesis might be that increasing degradation in ride environment from some ideal condition does not unduly influence passenger rejection of a system until some critical condition is reached beyond which ride quality abruptly assumes a dominating and adverse influence. Only a few members of the group had positive feelings regarding possible influence of moderate changes in ride quality (but above the rejection condition) on customer choice and use of a travel mode.

NECESSARY TECHNOLOGY

Opinions of workshop team members were obtained on the following questions:

> To satisfy your business activities, what kind of ride quality technology information is necessary?

Describe, in order of priority, specific areas in which you consider substantial improvements are needed in ride quality technology.

A summary of needs, as developed from answers to these questions and from subsequent group discussion at the workshop, is listed in Table II in approximate order of overall priority. For a given vehicle mode, numerical ratings of priority are shown with check marks used to indicate needs considered to be significant but of lesser priority. (See next page.) Of the twelve specific needs listed in the table, the first eight are considered to be common needs for all modes of transportation while the remaining four are needs unique to only a few modes. The common needs will be discussed below with the exception of Guidelines and Criteria which will be treated in a separate section. The unique needs will be treated in the discussion of Additional Motion/Vibration Ride Quality Data on page 26.

Interactions Among Ride Quality Factors

For all modes of transportation, the comfort of a given ride situation generally is affected by a combination of factors. Definition of ride effects is required, therefore, not only of factors acting individually, but also of factors acting in concert. In ride quality research to date, a majority of studies have centered on individual factors both to gain a basic understanding of each ride environment building block and to keep within bounds the resources and time required for equipment, test procedures, and data analyses. Simulators for controlled experiments, designed to provide a realistic multifactor ride environment, are quite costly and often have limitations in the useful range of the variable. Studies involving operational vehicles can be carried out to include all factors in real world

Table II. Ride Quality Technology Needs

SPECIFIC NEED \ VEHICLE MODE	Air			Highway		Rail/Guideway			Mari
	CTOL A/C	STOL A/C	HELI-COPTER	TRANSIT BUS	INTER CITY BUS	AGT	URBAN RAIL	INTER CITY RAIL	
Guidelines and Criteria	1	1	-	1	1	1	-	1	1
Interactions Among Ride Quality Factors	5	1	2	✓	2	1	-	1	-
Non-Motion Ride Quality Factors	-	1	1	✓	-	1	1	2	-
Additional Motion/ Vibration Ride Quality Data	4	1	3	✓	4	1	3	3	1
Better Vehicle Dynamics Evaluation Techniques	2	1	4	-	3	3	-	1	3
Standards for Reducing/ Presenting Data	3	2	-	✓	4	-	-	3	-
Specification Standards	-	1	-	-	-	2	-	2	-
Technology to Carry Out Cost Sensitivity Studies	✓	-	-	-	-	1	✓	2	-
Effects of Varying Trip Duration	✓	-	✓	-	-	-	-	✓	-
Effects of Motions on Standing Passengers	-	-	-	3	✓	-	2	-	-
Effects of Vehicle Operator Inputs	-	✓	-	✓	✓	-	-	-	-
Effects on Passenger Task Proficiency	-	-	-	2	✓	-	-	-	-

1 signifies highest priority.
✓ signifies an important but unranked variable.

situations. Such studies, however, made under relatively uncontrolled conditions, require the collection of large quantities of data coupled with sophisticated data analysis to isolate with precision effects of individual factors and interaction effects among factors.

Non-motion Ride Quality Factors

Non-motion environmental factors are known to influence ride quality but have received little attention in ride quality research. A considerable body of technology exists for some factors (e.g., temperature, humidity, odors) applicable for non-ride conditions which may not be fully applicable for some ride situations. For example, one commuter aircraft operator, convinced that a relatively warm cabin temperature aggravates ride discomfort caused by motion, reduces cabin temperature to below the normal comfort range whenever the aircraft is expected to encounter turbulent air. Transport system operators are often inclined to crowd many passengers onboard their vehicles with the result that seating space can be marginal. Crowded conditions, while acceptable for a short duration ride, can become very uncomfortable for a trip measured in hours. Thus, seat size and legroom factors are important. Noise is also becoming an increasingly important factor for new vehicles or candidate modes of travel (e.g., air cushion vehicle, powered-lift aircraft). A more detailed discussion of non-motion factors is given in the recent paper by Conner.*

Additional Motion/Vibration Data

For most vehicles, ride quality is very significantly, if not dominantly, influenced by vertical and lateral motions and vibrations. A great majority of the research effort has been directed toward study of these two factors. ISO Standard

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*Conner, D. W. "Non-motion Factors Which Can Affect Ride Quality." Proc. 1975 Symposium on Ride Quality, NASA TM X-3295, DOT-TSC-OST-75-40, page 87.

2631-1974(E) "Guide for the Evaluation of Human Exposure to Whole-Body Vibration " is a product of such effort. Various general needs for more motion/vibration data cited by the group included: effects of combined frequency conditions such as occur in the real world; effects of very low frequencies (0.1 to 1.0 Hz) where kinetosis (motion sickness) occurs; and effects of other degrees of freedom (e.g., roll, longitudinal), especially in combination with the vertical and lateral modes. Specific needs cited peculiar to certain vehicle modes included: effects of jerks for various seat orientations (e.g., AGT vehicle); effects of trip duration which become important for travel modes lasting more than a fraction of an hour; effects of motions on standing passengers (e.g., transit bus or urban rail); effects of vehicle operator (pilot, driver) inputs (e.g., bus modes and some air modes); and effects of the ride environment on passenger task proficiency (e.g., reading newspaper on a transit bus).

Better Vehicle Dynamics Evaluation Techniques

A need was identified for improved techniques to define the dynamic ride environment experienced by passengers from perturbing inputs to the vehicle. Motion-related inputs can be in the form of fluctuations in the medium surrounding the vehicle (e.g., air turbulence or ocean waves), waviness in fixed surfaces over which ground vehicles travel (e.g., rail tracks or highways), or commanded changes in vehicle direction or motions (e.g., turns or banks). Techniques must be appropriate to convert these inputs into dynamic forces acting on the vehicle and then to calculate the resulting dynamic environment at the passenger location. Needs include equations of motion appropriate for each type vehicle acting either as a stiff structure or as an elastic structure. Effects of passenger seat transmissibilities are also important since seats can either amplify or attenuate dynamic motions depending on seat characteristics and motion frequency. Special considerations are required for various

mode-unique problems. For example, the dynamic behavior of surface vehicles can be strongly influenced by the dynamic behavior of the roadbed or railbed on which vehicles travel, particularly where the bed structure is elevated or suspended. For marine vehicles, the response of vehicles must be determined not only for the normal modes of operations but also for cresting and broaching modes. Noise-related inputs involve essentially the same considerations as motion-related inputs except that the discomfort regime generally occurs at considerably higher frequencies.

Standards for Ride Technology

Because of the relatively underdeveloped or recently developed nature of ride quality technology, a lack of consistency exists in the manner in which experimental data have been obtained, quantified and reduced to useful form. Of great benefit to both the researcher and to the user would be greater standardization of conditions on which the ride technology data base is founded. Measurement of the ride environment not only involves selection of the particular factors to be measured but also how those measurements should be obtained. For example, valid reasons exist for measuring dynamic motions either on the vehicle floor or on the seat surface under the passenger. The state of the art has not yet identified single preferred measures of the dynamic environment (e.g., rms accelerations, peak values, spectral distribution, absorbed power, etc.). Lack of consistency also exists in the manner subjective evaluations of ride environments are made. This difficulty is aggravated by the complexities associated with quantifying human reactions to psychophysical stimuli. The lack of consistency in measuring and reporting both objective and subjective data has resulted in the generation of pockets of knowledge which have no common grounds for comparison.

Thus, the emerging technology base is not coherent. Greater standardization would also lead to development of more appropriate design specifications for vehicle systems. Compatibility of measurements and data parameters used both in research investigations and vehicle specification/performance undertakings are desirable.

Technology of Cost-Sensitive Studies

Application of ride quality technology to almost any situation requires consideration of cost implications. In a majority of situations, improvement in ride quality requires additional costs (e.g., vehicle construction, guideway construction, and system maintenance) which can be substantial in magnitude. The user therefore must be given a means to establish cost/benefit tradeoffs with relation to improved ride. For any one individual, there is no sharp demarcation between comfort and discomfort in the input level of a ride perturbing factor. This lack of demarcation, together with the great variability among people in comfort assessment of any given environment suggests that the technology must provide information relating to the degree of comfort experienced by cumulative fractions of the riders. Since some degree of ride discomfort is generally acceptable, depending on the situation, information is also needed which relates levels of ride comfort to a satisfaction evaluation in the context of the overall trip. Thus, the percent of passengers satisfied with the ride versus the cost of providing the ride can be quantified so that the desired cost effectiveness can be determined.

Effects of Varying Trip Duration

As trip duration can vary from a few minutes to many hours, a need exists for relating trip duration to ride effects. One effect concerns the change with time in the

sensitivity of travelers to specific ride environments. There is evidence that, depending on the ride environment factor, the perceived level of ride comfort may be either improved or aggravated with the passage of time. The minimum acceptable configuration for comfort factors, such as seating and roominess, of a vehicle could well be a function of trip length. A second effect concerns the manner in which passage of time affects the importance of a given ride event in the passenger assessment of ride quality and satisfaction for the overall trip. The remembrance of events oftentimes tends to be downplayed or even lost with the passage of time for non-ride situations. This "forgetting" effect may apply as well to trip comfort and/or satisfaction appraisal of a specific mode of transportation when the time comes to take another trip.

Effects of Motions on Standing Passengers

Very short-haul vehicles such as automated guideway transit, transit buses, and urban rail are configured to accommodate a large percentage of standing passengers. Such passengers are more sensitive to motion inputs from the vehicle than if they were seated. Obviously for systems employing such vehicles, special needs exist for ride quality technology applicable to standing passengers.

Effects of Vehicle Operator Inputs

The manner in which a vehicle is operated (e.g., accelerated, turned, etc.) can significantly influence the ride. Except for automated systems, vehicles are controlled by operating personnel and ride is thus dependent on human inputs with their attendant variability. Short haul systems, such as city buses which involve many stop-and-go and turn operations,are particularly sensitive to operator inputs. Special needs exist for ride quality technology,

both to design vehicles which are relatively ride-insensitive to operator inputs, and to train personnel how best to minimize ride discomfort while carrying out their assigned job of operating the vehicle.

Effects on Passenger Task Proficiency

Passengers generally desire the ability to carry out a few simple tasks while riding in vehicles. These tasks can range from reading while commuting to eating or writing for longer haul trips. A few members of the group cited the need for information pertinent to the effects of various ride environment factors on the proficiency of passengers to carry out such tasks when riding public transportation. The recognized and very important needs of military or business personnel who are required to carry out complex and exacting tasks while riding in vehicles were considered as beyond the scope of the present activity.

RIDE QUALITY GUIDELINES AND CRITERIA

The workshop team identified the greatest need in ride quality technology to be improved guidelines (suggestions for achieving objectives) and criteria (standards of judging). They are considered as playing a very important role in the specification, design, acceptance, operation and maintenance of advanced transportation systems. Where optional models of travel are available, assistance in the form of guidelines is needed to design and operate systems salable to the traveler. Such salability could be critically important, for example, when and if new energy-conservative systems are offered to the public. Where a free choice of travel mode does not exist, advantage could be taken of the public. In such a situation, acceptability levels of ride comfort would seem to be of public interest and subject to specification in the form of criteria (similar to requirements imposed in the field of safety).

Ride Quality Guidelines

The several guideline needs identified by the workshop team centered around information appropriate for cost/benefit studies. Achievement of ride quality completely comfortable to all travelers is not practical either from technological or cost considerations. Tradeoffs must therefore be made between that which is desirable and that which is practical.

In the area of "cost" technology, information is needed to quantitatively define the change in ride environment which results from a change in the vehicle system physical components or operations. For design purposes, the physical system and operations need to be defined and modeled in a form appropriate for use as a transfer function to relate input perturbations to the output ride environment.

In the area of "benefit" technology, information is needed to quantitatively relate change in passenger comfort, acceptability, and use of a transportation system which results from a change in the ride environment. Passengers do not all react the same for a given ride environment. Thus, information is needed to appropriately address any expected ride environment event and define the breakdown (by percentages) of expected passenger ratings according to the degree of comfort experienced. Furthermore, information is needed concerning the relationship between degree of ride comfort and passenger satisfaction with (and acceptance of) the ride. It must be recognized that satisfaction may be influenced by other factors, such as traveler expectations, which could differ from one mode of travel to another. Since the level of ride comfort can vary significantly during the course of a single trip, technology is also needed for integrating the predicted passenger reactions for a series of individual ride events which comprise a trip, into a predicted overall trip ride reaction.

Ride Quality Criteria

The workshop team addressed the following questions:

What form or forms of guidelines/criteria do you find, or would you find particularly useful?

What problems have you encountered, or anticipate, in establishing and carrying out a process to verify, for contractual purposes, that system performance meets design criteria previously specified?

Three distinct types of criteria were identified and evaluated with regard to attributes and shortcomings. Evaluations are listed in the following table.

Table III. Criteria Attributes and Shortcomings

Criteria Type	Attributes	Shortcomings
As Good As (AGA)	Related to Known Vehicles and Response of Passengers to Rides of These Vehicles Easy to Specify Covers All Factors of Environment	Determination of Compliance Difficult Uncertain Application to New Vehicle Types Cost/Benefit Trades Difficult
Not-to-Exceed (1974 ISO-2631 Standards)	Easy to Specify Values Frequency vs. Acceleration Curve Shape not Arbitrary Easy to Verify Compliance	Go/No-Go Limits Only Limited to Vibration Applies to Linear Degrees of Freedom Only >1.0 Hz Frequency vs. Acceleration Curve Levels Arbitrary
Output-to-Input Relationship	Easy to Express Vehicle Specifications Easy to Verify Compliance	Specifications Not Directly Related to Ride Comfort

A major shortcoming of the much used As Good As (AGA) criteria concerns the limited information provided about acceptable intensities of each factor in the multifactor environment of the vehicle under judgment. No allowance is made for tradeoffs

between factors (i.e., a favorable comparison of one factor could offset an unfavorable comparison of another factor). The AGA criterion can be useful only when there is sufficient similarity between the new and the comparison vehicle to warrant use of the comparison vehicle as a reference. Finally, use of AGA criteria makes difficult the specification of a level of ride quality either some degree better than or poorer than that of the comparison vehicle.

Unlike the AGA criteria, the Not-To-Exceed criteria form was judged to have no inherent shortcomings if appropriately structured but to have substantial shortcomings if too abridged. This form of criteria is relatively easy to specify and easy to verify and can be developed from well documented technology. The abridged form of the criteria employed in ISO Standard 2631 does have shortcomings as listed in the table. These shortcomings will be discussed both to point out specific improvements needed in ISO-2631 and to provide general illustration of the type of information needed for appropriately structured criteria.

Go/no-go limits are satisfactory only if qualified to account for the unusual events and/or for the variability among passengers in subjective comfort evaluations. Qualifications could be in the form of "not to be exceeded more than x percent of the time" and/or "to provide a satisfactory ride for at least y percent of the passengers." Limiting the criteria to only one or two factors (e.g., vibration) is not adequate if other factors (e.g., noise) which significantly influence ride comfort are present. Different types of vehicles have different combinations of factors which significantly affect ride comfort. A need exists therefore for criteria applicable to all appropriate factor combinations. The criteria should also be applicable to the variables within

each factor but this is not the case for the ISO criteria which addresses the vibration (motion) factor. The criteria are limited to linear degrees of freedom, to motion frequencies only above 1 Hz, and do not handle motions other than sinusoidal motion very well. At present, therefore, they are too restrictive for the real-world vibration/motion environment of vehicles. Criteria should be based on valid ride comfort data rather than data obtained for some other purpose. For the ISO criteria, the levels specified were an arbitrarily chosen fraction of levels experimentally established as appropriate for ensuring safety and performance capability of man in an industrial work environment. The authors of ISO 2631 tacitly recognized the various shortcomings with the statement that its first purpose is "...to facilitate the evaluation and comparison of data gained from continuing research in this field" and only second "...to give provisional guidance as to acceptable levels of human exposure to whole-body vibration."

Output-To-Input criteria, which are a relatively new form of criteria as applied to ride quality, focus on the vehicle transfer function and are independent of levels of either the input perturbations to vehicle or the output ride environment experienced within the vehicle. Contractually, specifications are thus very easy to express and compliance is relatively easy to verify. The principal difficulty centers on relating the specifications to some target level of ride comfort. A reasonably good definition is required of the expected input environment perturbations to the vehicle transfer function, and of the passenger transfer function (which relates the ride environment to passenger ride comfort). Output-To-Input criteria appear attractive for application to wheeled-vehicle systems where the vehicle rolls over a roadway or track which is built and maintained

by others. The magnitude of the input perturbations to the vehicle through its wheels can be treated as a known quantity dictated by criteria for roadway/track construction and maintenance.

TIMEFRAME FOR TECHNOLOGY APPLICATION

Workshop participants established a general timetable of needs for application of ride technology. The timetable was based on anticipated schedules for development of major new systems which would benefit from advances in improved ride technology. The schedule presented below underscores perceived need of the workshop participants for immediate enhancement of ride technology.

Table IV. Timetable of Technology Application Needs

Major New System	Technology Anticipated Need Date
Advanced People Mover	1975
Advanced Transit Bus	1976+
Long Haul Helicopter	1976+
Improved Intercity Train	1978+
Fuel Conservative CTOL	1977-1985
High-Speed Intercity Bus	1980+
Powered Lift STOL	1980-1985

MEETING OF THE TECHNOLOGY NEEDS

After identifying various technology needs of the transportation community, the workshop team discussed approaches concerning how best to implement research to meet these needs. General agreement was reached that combined effort of the industry, government and university communities would be required for a number of years. Effort directed toward generating technology was also

viewed as needing an additional catalyzing effort to effect progress in a systematic and timely fashion. This catalyzing effort was considered particularly important to identify and advertise to the technical community (both using and generating technology) the high priority needs, and to disseminate technology as it becomes available. In this regard, the broad field of ride quality technology was considered to suffer at present from a lack both of communication between interested parties and of an information clearinghouse. Also needed is the identification of resources to implement the required research. Technology user organizations traditionally are reluctant to fund research in advance of their needs. Government organizations have but recently sponsored ride technology research in any depth and then only in limited areas.

WORKING GROUP III - RIDE QUALITY RESEARCH TECHNIQUES

This group decided to divide itself into two sections:

3a. Section on General Techniques

3b. Section on Scaling Techniques

Thus the two reports prepared by the chairmen of each section are presented separately.

Group 3a. Section on General Techniques

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1.0 INTRODUCTION

The purpose of the Workshop Group on Ride Quality Research Techniques was to gather information about the methods currently used for the study of ride quality in a variety of transportation modes by a variety of research organizations, including universities, Federal agencies, contracting firms, and private industries. The report of this Group has been compiled as a guide offering detailed descriptions of these techniques and their strengths and weaknesses, and identifying the organizations using such methods. The specific efforts of the Group's participants, as well as a variety of feasible approaches not currently in use, are presented as methodological alternatives under the three basic factors which must be considered in ride quality studies: research techniques, research environments, and choice of subjects.

2.0 THE GOALS OF RIDE QUALITY RESEARCH

In order to assure a common orientation to the issues which must be addressed by ride quality research, participants discussed the various purposes of conducting such experimentation. It was agreed that research efforts should be directed toward four main goals:

1. Understanding human response to vibration, acceleration, noise, and all other physical inputs which contribute to the total ride environment;

2. Establishing design limits for relevant ride quality variables;

3. Establishing health, safety, and performance limits for these variables; and

4. Establishing the importance of ride quality in the public value structure.

In addition, four problem areas to which ride quality research could make a significant contribution were identified. These "meta" needs include:

1. Increasing the utility of transportation systems to the user population;

2. Maximizing military efficiency, where this is dependent upon use of transportation systems;

3. Investigating the mechanisms and functions of the vestibular system, its role in subjective ride quality assessments, and the incidence of vestibular pathology in the user population; and

4. Furthering the general goals of science in increasing human understanding.

3.0 ANALYTICAL TECHNIQUES USED IN RIDE QUALITY RESEARCH

Three analytical techniques commonly used to determine the level of ride quality achieved by a system were discussed.

3.1 The "As-Good-As" Method

The "as-good-as" method is perhaps the most commonly used method of determining the level of ride quality of a new system. This technique involves the comparison and matching of a new vehicle's ride comfort to that of an existing vehicle which has already been judged as acceptable.

The "as-good-as" method is quite familiar to members of the transportation community involved in ride quality testing, thus establishing a common ground for discussion of the relative merits of specific vehicles and systems.

A second advantage of this technique is that it yields a relative standard of ride quality which takes advantage of past experience. Thus, the results of using the "as-good-as" method may be fairly realistic and predictable.

There are also several disadvantages to using the "as-good-as" method which merit some discussion. Unless the critical variables which determine ride quality (linear and angular accelerations, velocity, track conditions, etc.) are specified, results obtained using this method on different vehicles cannot be compared.

The "as-good-as" approach cannot realistically be used in the evaluation of new systems or new transportation modes. The factors other than ride motion which contribute to making the standard vehicle "acceptable" can be so different that a profoundly different type and level of ride motion may be required.

Perhaps the most significant problem with the "as-good-as" technique is that it limits or eliminates the possibility of estimating and implementing cost "trade-offs" between ride motion and other aspects of system costs. It is entirely possible that basing ride requirements on a smooth-riding existing vehicle, designed during a period when energy utilization was not cri-

tical and vehicle mass was relatively unconstrained, might place ride requirements on new vehicles which cause needlessly elevated costs for guideway and suspension acquisition and maintenance.

3.2 The Absolute Standard

A second analytical technique discussed in the Workshop was the absolute standard of ride quality. The absolute standard approach specifies that indices of ride quality must not exceed certain set limits. The absolute standard of ride quality which limited highway surface deviation to 1/8 in. per 10-foot stretch of untextured road was used for many years by the Federal Highway Administration. If deviations in a stretch of highway exceeded this level, the contractor was required to rebuild the road. Since modern textured road surfaces may have grooves exceeding 1/8 in., a rolling straight edge on the front of a truck is currently used to determine if highways achieve the absolute standard of ride quality set by the FHWA.

It was concluded that while other modes of transportation could develop absolute standards, this would require ride quality analyses of existing systems to determine a realistic level of comfort for future comparisons. Developing an absolute standard based on acceptable ride quality levels in older systems would therefore be the same as using the "as-good-as" method in its present form, with all the concomitant problems of the latter technique.

Perhaps the most ambitious attempt at developing standards has been that of the International Organization for Standardization Guide for the Evaluation of Human Exposure to Whole-Body Vibration (ISO 2631)[1]. This document suggests the maximum permissible levels of motion amplitude at various frequencies for three conditions: safety, interference with work, and comfort. In the sense that the guidelines were developed based on experiments with human subjects and without regard to the systems which produce the motion, they are absolute

standards. However, the document notes that, with regard to comfort, the motion levels permissible can vary considerably, depending on the system that produces the motion and the passengers' acceptance of the system. The use of the ISO comfort curves in conjunction with investigations of system acceptability will permit the development of cost trade-offs.

3.3 <u>The Input-Output Method</u>

The input-output method is based on the assumption that a certain input value of a physical variable yields a certain output value in terms of ride quality. The input-output method is currently used in assessing the ride quality of marine systems. For instance, a certain value of sea state would be expected to yield a certain rms g value of acceleration, which is considered an index of ride quality. Use of the input-output method allows for the prediction of ride quality resulting from certain variables which determine the motion environment, such as sea state or track condition. However, it is difficult to specify relevant variables to be used on the input side of the equation. Also, the input-output method must be used in conjunction with the absolute standard, since the former method does not independently specify an acceptable level of ride quality.

4.0 <u>RIDE QUALITY RESEARCH TECHNIQUES</u>

4.1 <u>Scaling</u>

Scaling techniques are concerned with the measurement of ride quality subjective responses obtained from passengers and others who may be involved. They are of great importance to the validity of the research and are also of a very specialized nature. Hence a special Group was established to consider this subject. The report of this panel is presented separately, beginning on page 65.

4.2 Performance Assessment

According to John Guignard of NAMRLD, little research has been done on the sensitivity of human performance to vibration which would be relevant to the complex ride environments involved in present-day ride quality research. Two important aspects of human performance which have been largely neglected by past research are:

1) degree of performance degradation with time; and

2) the respective roles of central and peripheral processes of the human nervous system, as these contribute to performance deterioration in the vibrational environment.

Fatigue-induced performance decrement in a vibration environment remains an unproven phenomenon; the study of these effects is nevertheless important to the validation of the ISO 2631 (1) "fatigue-decreased proficiency boundary."

In situations of severe vibration, it is advisable to use animal subjects. However, the use of human subjects is encouraged whenever possible to provide more authentic analyses of the performance variables encountered in various modes of transportation.

4.3 Medical Research

4.3.1 Biodynamics

Guignard emphasized the importance of biodynamic research in the solution of ride quality problems. The motion or force measured in most ride quality research efforts must be related to a definable biodynamic coordinate system based on bony landmarks of the human body. If force inputs and points of entry into the body can be defined, it might be possible to locate the terminal effects of vibration within the human body. Captain C. L. Ewing of the Naval Aerospace Medical Research Laboratory has developed this sort of biodynamic method for the U. S. Navy's impact program.

Although biodynamic research as it relates to ride quality was not discussed at length in the Workshop, it should be emphasized that the use of human subjects under tolerable vibration limits is strongly recommended. Animal biodynamic coordinates can be extrapolated to humans only to a limited extent; the use of animals should therefore be avoided whenever possible.

4.3.2 Physiology and Pathology

Dr. Walter Johnson, an otolaryngologist at the University of Toronto, discussed the relationship between vestibular effects, including disorientation and motion sickness, and ride quality. In particular, he emphasized that vestibular effects may influence passenger comfort and feelings of well-being, as well as crew efficiency in a variety of transportation systems.

Research on human and animal subjects in the medical laboratory has revealed two deep physiological changes which occur in vestibular sickness. First, there is a shunting of blood out of systemic circulation and into the skeletal muscles, resulting in the characteristic pallor of motion sickness victims. The amount of blood reaching the brain may be insufficient to maintain alertness; therefore, yawning and sleepiness may occur. A second type of deep physiological change which often accompanies vestibular pathology is the antidiuretic effect. It has been shown in medical laboratory research that subjects who are heavily hydrated and nauseated by rotation with superimposed head motions lose the ability to eliminate urine. The magnitude of antidiuretic effect varies from subject to subject, but remains proportional to the degree of nausea experienced. Feelings of well-being may be influenced in human subjects by the ability to urinate. In addition, a chemical has been discovered in the urine of vestibular sickness victims which seems directly related to the degree of pathology. When this chemical was injected into rats,

it produced an antidiuretic effect. The posterior pituitary gland has been implicated as the source of this endocrine disturbance.

Laboratory research using primates has also shown that intense sound (145 dB) of long duration at high frequencies (4000 Hz) may cause dizziness, nystagmus, subjective vertigo, ataxia, and vomiting. Noise of this type may disturb vestibular mechanisms of the inner ear and can actually destroy the vestibular organs.

Medical research into the physiological aspects of ride quality has not yet determined the general labyrinthine sensitivity of the population as a whole. Recent evidence suggests that there may be great variability between individuals in terms of this sensitivity--in fact, no two individuals may be alike, and no individual may react in exactly the same way on successive exposures to a uniform motion environment.

Johnson also described a variety of techniques for measuring vestibular response to motion. Many of these techniques involve the use of simple motion simulators. It has been shown that while linear vertical acceleration can produce motion sickness (2), these effects can be eliminated by fastening subjects' heads to the backs of their seats (3).

It must be remembered that the vestibular organs are located in the head, which rarely experiences the same vectors of motion as the rest of the body except when the subject is lying in a prone position. The use of head-mounted accelerometers in ride quality research is therefore encouraged.

A second type of medical laboratory research using a motion simulator was conducted to determine the reason student pilots in the Air Force experience motion sickness. A two-pole swing producing sinusodial back-and-forth motion at a frequency of .5 Hz was found to cause motion sickness. When

a spot of light was attached to the subject's head and a camera was mounted on top of the swing, it was found that the head does not move with the motion of the swing. These results again point out the discrepancy between head and body motion in a ride situation. It was also found that the degree of wakefulness, the mass of the head, and the tonus of the neck were important factors in determining susceptibility to motion sickness. No two individuals reacted to the two-pole swing motion in the same way, and no individual reacted identically on successive exposures to this type of motion.

The two-pole swing produced motions of the head in both the lateral and vertical axes at the same time; when the head was fastened and therefore moved in only one plane, no subject got sick. It was therefore concluded that head motion in two planes at once is an important factor in causing motion sickness.

Cross-coupled angular accelerations of the head have also been found to cause motion sickness. When linear and angular accelerations are presented at the same time, both the otoliths and semicircular canals (the vestibular organs responding to linear and angular accelerations) are stimulated at once. Again, the result is motion sickness. Head movements that are rhythmic do not cause as much vestibular disturbance as irregular head movements. Square wave head movement plus accelerative motion in a secondary plane also produces nausea and disorientation.

The off-vertical rotation procedure, in which the head is strapped down and the subject is rotated in a chair off the vertical axis, does not characterisitcally cause motion sickness. The barbecue-spin rotation method, in which the subject's body is spun around the horizontal axis, does cause motion sickness. Since the vertical gravity vector changes while the subject is spinning in the latter situation, two linear accelerations are experienced by the subject at the same time, resulting in adverse vestibular effects.

The results of physiological studies and simple motion simulator research in the medical laboratory point out the importance of head motion in inducing motion sickness. It may be concluded from these studies that comfortable and efficient transportation of passengers with pathological vestibular states requires keeping their heads immobile. Also, future ride quality research should address the problem of cross-coupled accelerations of the head in two or more planes.

In the future, space flights may provide an excellent ride quality research environment in which to study the effects of pure linear stimuli on motion sickness, since the gravity vector is absent in outer space. These flights would provide an excellent opportunity to acquire a basic knowledge of how the otolith is stimulated.

4.4 Public Opinion Surveys

In a presentation of public opinion sampling methods, Dr. Michael Kavanagh, Associate Professor of Management at SUNY, Binghamton, New York, emphasized the importance of utility variables (safety and security, cost, convenience of access) and psychological comfort variables (territoriality, perceived prestige of riding in a system, characteristics of fellow passengers) in public perception of ride quality. According to Kavanagh, the primary concern of ride quality research is to study the choice, or decision-making, behavior of the traveling public relative to the various available modes of transportation, and to discover the factors which contribute to the decision to ride again. Variables related to utility and psychological comfort may interact with aspects of physical comfort to determine these choices. Yet these variables have not been thoroughly investigated and are not commonly included in current definitions of ride quality.

Public opinion surveys are a powerful research technique which may be used to assess the needs and values of the trav-

eling public with respect to ride quality. Kavanagh discussed the relative merits of three types of research groups which may be used to conduct such surveys:

1) Academicians in universities are generally well acquainted with scaling methods and sampling theory, and are able to design surveys and sampling plans. However, they are often reluctant to become involved in the mechanics of surveying procedures, do not perform well under contract arrangements, and may feel constrained in an applied research situation.

2) Large survey organizations involved in sampling on a nation-wide basis (e.g., Roper, Gallup, and Survey Research Center at the University of Michigan) are well-equipped to provide demographic and attitudinal information about the sample, in addition to data on the specific interests of the subscriber. Unfortunately, the cost of running such surveys is very high--approximately $20,000 for five minutes of interview time. Also, determining public opinion on ride quality of a given transportation system or mode usually requires sampling from specific populations in a limited geographic area; national sampling is generally not necessary.

3) Consulting firms are often used to conduct public opinion polls and are generally quite good at meeting contractual deadlines and designing surveys for any given purpose or population. There are, however, several different types of consulting firms, each with its own particular advantages and disadvantages for opinion surveys on ride quality.

(a) Psychological consulting firms do not consider surveying as part of their main business. Thus, although these organizations may have staff members who are competent in opinion sampling, they may have little experience, and should be carefully investigated before selection.

(b) Management consulting firms typically do not retain staff members with expertise in public opinion surveys, and may sub-contract such work to other consultants. As with psychological consulting firms, opinion sampling is not their main concern, and caution should be exercised before awarding them a contract for a public survey.

(c) Market research consultants are probably the best sources of opinion sampling surveys for ride quality research. These organizations specialize in public opinion sampling, and retain entire staffs devoted to survey development and sample design. They have both expertise and experience in the areas of scale development, definition of the target population, sampling design and execution, and mail, telephone, or personal interviews as sampling techniques. In addition, they can conduct both laboratory and field work where the research problem requires it.

5.0 RIDE QUALITY RESEARCH ENVIRONMENTS

5.1 Motion Simulators

Sherman Clevenson of the NASA-Langley Research Center presented a brief review of a variety of motion simulators currently being used for ride quality research. The motion capabilities and interior environments of airborne and land-based simulators were discussed, as well as the advantages and disadvantages of using such devices in ride quality research.

5.1.1 Airborne Simulators

The Lockheed Jet Star Simulator is a four-engine aircraft which seats two people, one at the center of gravity and one in the front of the plane. The particular Jet Star discussed was bulit to simulate other kinds of aircraft for training purposes but may be used for ride quality studies as well.

Lateral and vertical accelerations, and pitch and roll may be simulated. One disadvantage of the Jet Star is that it makes its own noise rather than reproducing that which is characteristic of the vehicle to be simulated.*

A second type of airborne simulator is TIFS (Total In-Flight Simulator), which was also built to simulate the motion and operational characteristics of a wide variety of other aircraft. It produces some motion in five degrees of freedom, and at low frequencies outputs can be controlled by an electronic tape system. (Steady-state effects produced by TIFS were previously discussed in the Ride Quality Symposium by W. Elliott Schoonover.) TIFS is fairly realistic, and ten passengers can be accommodated in the cabin. A variety of different design features and their relations to ride quality may be explored using this simulator.

5.1.2 Land-Based Simulators

The simple shake-table type, which produces motion but no visual input, was used as the basis of research such as that of Pradko and Lee on absorbed power (4). The device, used to simulate a tank, was basically intended to be used in tests of task adaptability and task interference. It was not constructed for use in ride quality research. Simulators available at the Wright-Patterson Air Force Base have also been used by test pilots performing a variety of operations in a simulated motion environment. In the Wright-Patterson simulators, random noise may be input to the subjects through earphones. These simulators were originally intended for vibration tolerance work rather than ride quality research. Other simple flight simulators include a pulley-operated device made

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*As far as can be determined this aircraft, operated by the NASA-Flight Research Center at Edwards, California, is not now airworthy.

by Grumman Aircraft which can produce vibrations below 3 Hz. No ride quality research has yet been conducted on this simulator. Northrop-Boeing has also used aircraft simulators to study human response to supersonic transport motions.

Among the more sophisticated motion simulators is the Langley "Spider" (Langley Visual Motion Simulator). The "Spider" rests on six legs and can simulate motion in six degrees of freedom. This simulator has basically been used for pilot training and man-machine studies. The Rendezvous Docking Simulator can also produce vibrations in all six degrees of freedom. This device has been used to train astronauts and to conduct the ride quality studies done by the University of Virginia on light aircraft motion. The Rendezvous Docking Simulator hangs in space and provides no visual cues to subjects.*

The only motion simulator which has been constructed and used specifically to reproduce some of the relative motions of a passenger ride is PRQA (Passenger Ride Quality Apparatus). PRQA simulates motion in three degrees of freedom (roll, vertical, and lateral motion), and has four windows, speakers, and screens which may be used for visual inputs. It can reproduce multiaxis motions of variable frequency and displacement below 30 Hz. The PRQA can also withstand impact, and could feasibly be used to study tolerance of crash motions.

5.1.3 Advantages and Disadvantages of Simulators

Of all available ride quality research environments, it was felt that the simulator provides the most flexibility in terms of the types of motions which may be reproduced. The degree of experimental control provided by the simulator was

*No longer available.

also considered one of its benefits. In many cases, simulators are relatively low-cost alternatives in which to conduct experimental studies of ride quality, particularly in the cases of air and marine transportation systems. Finally, of all available ride quality research environments, simulators provide the maximum degree of safety to the subjects.

Among the disadvantages of using simulators in ride quality research, a lack of fidelity was felt to be a major problem.* In real vehicles, passengers and operators are exposed to random and sinusoidal motion rather than the pure sinusoidal motion presented in simulators. Secondly, the fixed location and lack of mobility of many motion simulators precludes their widespread use. Simulators are generally not available to the majority of ride quality researchers. Man rating is also a problem. This relatively long and complex process of insuring the safety of the subjects on the simulator makes rapid and inexpensive modification required to adapt the system to a variety of vehicles and rides difficult. Finally, it is not known whether subjects used in simulator research have the same expectations and motivations as passengers riding on actual systems.

5.2 Prototype Vehicles

Although no specific research efforts using prototype vehicles were discussed in the Workshop, the advantages and disadvantages of using this type of research environment were assessed. Among the advantages, it was noted that the prototype provides increased realism over the simulator, and permits subjects to evaluate the ride environment of the entire vehicle, including a variety of non-motion factors which are

*This question is being examined by comparisons of subject reactions to similar motion environments on TIFS and PRQA.

not effectively reproduced in any of the aforementioned simulators. Total ride acceptance may therefore be better assessed in prototypes. Also, research in the prototype environment may reveal unsuspected problems with the system which could not have been easily predicted beforehand.

Some disadvantages of using a prototype vehicle for ride quality research include the high cost of providing such an environment, especially in the testing of air and marine systems. Prototype vehicles may also provide situations of unrealistic quality control, in comparison to vehicles which ordinarily emerge from the production line. Also, as in the case with simulators, the availability of prototypes is often restricted.

5.3 Production Vehicles

Again, specific presentations of research using production vehicles were not offered by participants in this Workshop, but the pros and cons of using this type of research environment were discussed. One great advantage of using the production vehicle is that it is relatively easy to obtain a large number of subjects among the passengers who regularly use the system. Research in production vehicles allows for the assessment of variance between vehicles, and for comparisons between the ride quality of the vehicle in question and that of alternative forms of transportation. In addition, the effects of system deterioration and different operating conditions on subjective and objective measures of ride quality may be determined.

Although the production vehicle is probably the most realistic research environment, it offers the least opportunity for strict experimental control. The agency responsible for the operation of the vehicle may place restrictions on the survey methods and instrumentation which the experimenter may use. Finally, there may be sampling problems in this type of

research environment since it may be difficult to obtain a realistic representation of the total passenger population in terms of the relevant demographic variables.

5.4 Medical Laboratory

Specific examples of ride-quality-related medical research on the physiology and pathology of the vestibular system were summarized by Dr. Walter Johnson, and are described in Section 4.3.2. In addition, investigations of bio-dynamics and performance degradation due to vibration could feasibly be conducted in the medical laboratory environment, using captive subjects, patients, and animals. Surveys of patient's subjective responses to motion might also be conducted; however, the results of such studies would be of limited application, considering the highly specific characteristics of the subject sample.

Because the medical laboratory is used for research of a highly specific nature, it does not constitute a real "choice" in terms of ride quality research environments. When vestibular pathology and the physiological aspects of behavior are of relevant interest to the ride quality researcher, the medical laboratory is the only research environment which will suffice. It also provides the only research situation in which in-depth analysis of the effects of motion variables may be conducted using surgical and pharmacological techniques. Although such research is expensive and often applicable only to a small and highly specific user population, it can offer insights into the mechanisms by which humans assess ride quality, therefore making a significant contribution toward achieving an understanding of human response and fulfilling the needs of Science.

A summary of the advantages and disadvantages of using the various ride quality research environments is presented in Table I.

Table I

Advantages and Disadvantages of Ride Quality Research Environments

Environment	Advantages	Disadvantages
MOTION SIMULATOR	Flexibility Control "Low cost" Safety	Lack of fidelity Lack of mobility Restricted availability Man rating Variable subject expectations
PROTOTYPE VEHICLE	Realism Evaluation of entire vehicle Ride acceptance Reveals unsuspected problems	Very expensive Unrealistic quality control Restricted availability
PRODUCTION VEHICLE	Large sample size Exploration of variance between vehicles Operating conditions Deterioration Competitive position	Little control Restrictions on survey methods Restrictions on instrumentation Sampling problems
MEDICAL LABORATORY	Exploration of pathology Exploration of physiological aspects of behavior Use of surgical and drug techniques on animals	Limited subject population Very expensive

6.0 SUBJECTS USED IN RIDE QUALITY RESEARCH

The general classes of subjects used in the various research environments with a number of experimental techniques have already been casually mentioned in preceding sections of this Report. Research using the inanimate human simulator as discussed by William Park of Pennsylvania State University is described in detail below. In addition, the advantages and disadvantages of using various classes of subjects are summarized.

6.1 Captive Subjects

Captive human subjects are selected by the experimenter and paid for their participation in the research effort. Use of captive subjects offers the maximum in convenience and control to the experimenter, since they are at the researcher's disposal from the time they agree to take part in the research, and may be called back to the experimental situation for further testing. Captive subjects are usually well motivated, since they are being paid for their efforts. They can be trained to a standard level of proficiency in complex environmental tasks. Use of captives also allows for the maximum research design flexibility since they may be used in a variety of experimental environments, with a wide range of research techniques.

One disadvantage of using captive subjects is that it may create an artifically ideal experimental situation. Captive subjects must often pass rigorous physical examinations to insure their ability to withstand the motion stimuli presented in the experiments. Thus, they are usually in excellent physical condition, unlike ordinary passengers, whose health may be more variable. Research to assess acceptability, utility, and non-comfort aspectsof the ride cannot realistically be conducted with these captives. These subjects

may be inclined to please the experimenter and therefore tolerate more stressful physical inputs, or judge these as milder, than volunteers or subjects who are paying to ride.

6.2 Paying Passengers

Paying passengers are most often used as subjects in prototype and production vehicles for survey purposes; they can also be used to assess performance degradation. Use of paying passengers offers greater authenticity and applicability of the research to real-world problems. Paying passengers are also more realistically motivated than captives in the sense that their opinions and judgments represent their own value structure rather than a bias in favor of the experimenter. Non-comfort aspects of the ride, including cost and utility factors, may also be reliably assessed. Paying passengers most likely provide a wider and more representative range of values in terms of physical and demographic variables, thus increasing the chance of obtaining valid and useful results.

The disadvantages of using paying passengers include limitations in terms of the choice of research environments since motion simulators and medical laboratories are not generally used. It is difficult to control the behavior and other characteristics of such subjects, in terms of the relevant variables of the experimental situation. Test duration must generally be limited, and sampling procedures may require a large number of subjects to participate. Finally, the experimenter may be restricted by Federal agencies or the carrier regarding the questions which subjects may be asked, or the tasks that they may be required to perform.

6.3 Patients

Patients constitute the subject population for the study of human vestibular pathology and its effects on perceived motion in the medical laboratory. They can also be used for

surveys and biodynamic or physiological research and to assess performance degradation in production vehicles on a limited basis.

One advantage of using human patients for physiological and pathological research is that they are readily available to medical laboratories, and may agree to limited surgical and pharmacological manipulations. A relatively strict degree of experimental control is possible using patients as subjects, since medical histories and information about other potentially relevant variables have usually been collected by hospitals and caretaking institutions. Patients may also represent definitive cases and interesting "natural experiments" from which a significant amount of basic knowledge about mechanisms of human response to motion may be acquired. For instance, research on patients with varying or progressive degrees of vestibular pathology could answer the question of how subjective reaction to motion changes with the otoliths and semicircular canals present and absent.

Of course, patients represent a limited and highly specific population, and the results of research using such subjects for surveys and performance assessment are of limited applicability. Furthermore, the responses of patients may be influenced by pathology extending beyond the vestibular system, thus complicating interpretation of the results.

6.4 Animals

There has been relatively little research done on animals in reference to ride quality problems except in the medical laboratory. Still, animal subjects constitute an unexploited but potentially useful resource for the ride quality researcher, since they may be used in experimental situations in which the use of humans would be judged unacceptable. Animals can serve as subjects in vehicles or systems which

have not been man-rated and in dangerous environments such as outer space. They can be subjected to dangerous or extreme levels of vibration which destroy the vestibular organs, so that the upper limits of motion tolerance may be identified. Important physiological data may be obtained by sacrificing animals exposed to extreme stimulus levels, and histologically determining the sensory organs which have been damaged by the motion. Electrodes may be implanted in the vestibular organs to monitor neuronal response to varying levels of physical input. In addition to the surgical and pharmacological modifications which may be achieved with animal subjects, inbred strains may be used to reduce between-subjects variance for a finer degree of experimental control.

There are, however, some disadvantages which may limit the usefulness of animal subjects. First, animals cannot give verbal subjective reactions to the motion environment. Second, the results of any experiment using animal subjects require careful and conservative extrapolation to the human species. Finally, animals do not possess the same biodynamic and postural characteristics as humans. The results of research using animal subjects may therefore be of limited applicability.

6.5 "Human Simulator"

Dr. William Park of Pennsylvania State University discussed the principles of design and operation of a human simulator or "dummy." This simulator was designed to accurately reproduce the biomechanical response of a seated man of 50th percentile weight to vibrations of up to 20 Hz in two degrees of freedom. Seat interface accelerations of the simulator in a ride situation are converted to absorbed power, using the amplitude-frequency distribution technique. Correlations of absorbed power between human subjects and the simulator are good for random motion in the vertical plane between 1 and 10 Hz.

Of course, the usefulness of the Pennsylvania State human simulator is dependent upon the validity of the absorbed power model as an accurate physical correlative of ride quality. Park argued that absorbed power is logically related to the subjective response to vibration since it is a function of the elastic and damping properties of the human body. Pradko and Lee (4) used absorbed power to measure the tolerance thresholds of thirteen subjects to tank vibration and found it to be proportional to subjective reaction. Researchers at Pennsylvania State have used this method to rank roads according to roughness and to predict the comfort expected for a given vehicle, driven at a given speed over a specified road profile. Absorbed power was also highly correlated with subjective ride ratings for a bus driven over seventeen road segments. Because absorbed power is a scalar index, the effects of motion in a variety of directions may be summed, simplifying the relationship between the physical and subjective aspects of ride quality.

The Pennsylvania State human simulator has been criticized for its reliance on absorbed power, since this method is not actively used by many ride quality researchers at the present time, and for a variety of other reasons. Chief among them is the fact that absorbed power is equivalent to the amount of heat generated in a body due to motion. It cannot be and has never been directly measured. Absorbed power is actually an impedance measure; it cannot be measured accurately due to the effects of damping. In fact, the increase in body heat due to vibration may be so small as to be undetectable by modern measurement techniques. It was suggested that Pradko and Lee may have had success with the absorbed power method because they were concerned with extreme levels of vibration; other researchers using the absorbed power model to measure lower levels of vibration may have merely been

measuring instrument noise. Also, the absorbed power method is not valid when vibration frequency falls below 1-2 Hz, where the effects of motion on the vestibular organs become significant. Finally, the bulk of evidence shows that subjective ride comfort actually depends upon the local (resonance) effects of vibration, and not on total power absorbed by the whole body.

The advantages and disadvantages of the human simulator dummy were also discussed independently of the absorbed power controversy. Among the advantages, the simulator can generate easily reproducible data, given constant physical inputs. Results of simulator testing can be used to identify the specific physical characteristics of a poor ride, to a limited extent. The simulator is a likely "subject" for testing prototype vehicles which have not yet been man-rated. It also provides the strict subject control necessary to compare rides in different vehicles and by different agencies. Finally, the human simulator reduces the need for large numbers of subjects in the routine testing of production vehicles.

The disadvantages of using the simulator rather than actual human subjects include its limitations in terms of representing a realistically variable population of users. The weights and elastic and damping properties of the bodies of women (especially pregnant passengers), children, and 50% of all males differ from those of the simulator. Women have a significantly higher percentage of body fat than men, and this factor could drastically change the elastic and damping properties of the body. Also, the simulator provides no subjective opinion of the ride and cannot offer any information about the acceptability of the total ride environment other than in terms of absorbed power.

The dummy design accounts only for vibration and neglects the relevance of vestibular effects. A dummy with legs to

receive vibration inputs from the floor might be an improved design. Seat transmissibility should be measured and recorded, to provide a further source of relevant information for vehicle designers.

Finally, the validity of the present simulator's response in terms of absorbed power is at present limited to motion in one degree of freedom within a narrow frequency range. Hopefully, future versions of the human simulator will be able to remedy at least some of the deficiencies of the present dummy.

Table 2 presents a summary of the advantages and disadvantages of using the five general classes of subjects described above.

7.0 THE INTERACTIONS BETWEEN RIDE QUALITY RESEARCH ENVIRONMENTS, TECHNIQUES, AND SUBJECT TYPES

Table 3 represents the interactions between various levels of the three methodological dimensions of ride quality research discussed in this Workshop. (The Subject Choice dimension has been broken down by associating its various levels with the appropriate Technique/Environment combination so that the Table might be more comprehensible.)

8.0 REFERENCES

(1) "Guide for the Evaluation of Human Exposure to Whole-Body Vibration," International Standard ISO 2631-1974.

(2) Wendt, G. R., "N.R.C. USA Com. Av. Med.," Final Report, December 1945.

(3) Manning, G., "Failure of a Vertical Accelerator to Produce Motion Sickness," NRC Can. Rep. C2649, 1943.

(4) Pradko, F. and Lee, R. A., "Vibration Comfort Criteria," SAE Paper 660139 (1966).

Table 2

Advantages and Disadvantages of Subject Types in Ride Quality Research

Subject Type	Advantages	Disadvantages
CAPTIVE	Convenience Strict experimental control Well-motivated Versatility Can be trained and standardized for complex tasks	Subject bias Artificially healthy sample Not useful for testing acceptability, non-comfort factors
PAYING PASSENGER	Authenticity Accurately motivated Can assess non-comfort factors Wide range of physical characteristics	Not useful in simulators, medical laboratories Weak experimental control Limited duration of tests Sampling-large N required Restrictions on survey methods
PATIENTS	Availability for medical research Definitive cases "Natural" experiments Strict experimental control Surgical/drug techniques	Limited research environment Non-general subjective reaction Non-vestibular pathology
ANIMALS	Man rating unnecessary Dangerous stimulus levels Dangerous research environment Expendable Surgical/drug techniques Electrophysiological recording from central nervous system Can be genetically similar	No subjective reaction Species-specific results Non-human biodynamics and postures
HUMAN SIMULATOR	Easily reproducible data Man rating not required Compare rides across vehicles Compare rides by different agencies Ideal routine test subject for production vehicles	Absorbed power controversy Limited applicability as model of "average man" Non-subjective reaction Neglects vestibular effects No foot vibration input Seat transmissibility must be measured Validated only for 1 degree of freedom, 1-10 Hz

RESEARCH ENVIRONMENTS

RESEARCH TECHNIQUES	SIMULATORS	PROTOTYPES	PRODUCTION VEHICLES	MEDICAL LABORATORY
SCALING	✓ Captives	✓- captives, paying passengers	NA	NA
PERFORMANCE	✓ captives, patients, animals	✓ captives, paying passengers, animals*	✓ captives, paying passengers, patients	✓ captives, patients, animals
MEDICAL RESEARCH: biodynamics, physiology, pathology	✓ captives, patients, animals	✓ captives, patients, animals*, human simulator	✓- captives, human simulator	✓ captives, patients, animals
SURVEY	NA	✓- captives, paying passengers	✓ captives, paying passengers	✓ patients

✓: Feasible
✓-: Limited
NA: Not applicable
*: Unlikely but possible

SUBJECT CHOICES

- CAPTIVES
- PAYING PASSENGERS
- PATIENTS
- ANIMALS
- HUMAN SIMULATOR

Table 3. Interactions between Ride Quality Research Environments, Techniques, and Subject Types

Group 3b. Section on Scaling Techniques

PARTICIPANTS: Geoff Allen, RAE/Farnborough
Michael J. Clarke, University College of Swansea/University of Virginia
Glynn D. Coates, Old Dominion University
Thomas K. Dempsey, NASA Langley Research Center (Chairman)
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Raymond Kirby, Old Dominion University
Larry G. Richards, University of Virginia
Warren Torgerson, Johns Hopkins University

1.0 INTRODUCTION

The primary objective of this section was to review and evaluate scaling techniques appropriate for the measurement of ride quality subjective responses. Since the time allocated for the section was a single day, and the fact that a central theme of the discussion was an expression of divergent opinions, the summary that follows is not to be treated as conclusive in any fashion. In fact, relative to these diverse opinions there was voiced a need for a subsequent workshop. Since it would not be practical to relate the entire contents of the workshop due to these different opinions, major focal points of interest are summarized in succeeding paragraphs as follows: (1) Scope of Scaling, (2) Goal of Scaling, (3) Category Scales; including polarity, scalar points, and whether the scale is discrete or continuous in nature, (4) Need and Use of Adjectives and/or Adverbs, (5) Role and Use of Magnitude Estimation, (6) Multiple Response Measures, and (7) Related Topics.

2.0 SCOPE OF SCALING

A general consensus was that information regarding a multifactor physical environment is needed for the accurate prediction of ride quality. However, major attention within the discussion was selectively focused on the physical measures

of noise and vibration as representing the most critical parameters for this type of work. This discussion restriction was imposed due to time constraints, and to the belief that certain commonalities should exist between the scaling of these and other sensations.

3.0 GOAL OF SCALING

A generally agreed-upon purpose for scaling subjective responses is for a better understanding of the influence of vibration (and noise) on man, and a subsequent development of "limits" and "criteria" for improving the ride quality of current and future transportation vehicles. These criteria are generally conceived of as involving a comfort dimension (e.g., discomfort-comfort). However, G. Allen emphasized the need to subdivide the dimension of comfort into the three components of (a) emotional comfort-discomfort, (b) activity disturbance, and (c) physical discomfort. Although the majority of the workshop members recognized the value of such a conceptualization in order to understand human response to vibration, the first component (emotional comfort) was conceived of as greatest importance to ride quality research. Due to the large scope of potential comfort criteria, workshop members agreed, after much discussion, to restrict discussions to the "emotional" aspects of comfort that pertain to noise/ vibration environments. It was clear that further discussion of this matter should take place at some future date when inputs from work in both the U.S. and the U.K. would be available.

4.0 CATEGORY SCALES

The number of different subjective rating scales that have been used in ride quality research is enormous. These scales can be conceived of as varying according to: (a) scale type, for example whether the scale consists of boxes and is discrete in nature, or if the scale is of a line

variety and continuous in nature, (b) number of scalar points, which refers to the number (two or greater) of demarcations the subject is provided on the scale, (c) polarity, for example, whether the response requested can be recorded on a unipolar or bipolar scale, (d) physical length of the scale, and (e) adjectives and adverbs attached to the scale as a whole, or to demarcation points along the scale. The first four categories are addressed in the next section and the last category related to adjectives and adverbs is addressed in a subsequent section.

The results of several experimental studies addressing these scale characteristics were discussed. In particular, the preliminary results of a study of T. Dempsey provided a framework for these discussions. The consensus was that greater subject reliability was obtained with continuous rather than discrete (box) scales, and with 7 or 9 scalar points rather than fewer points. The case regarding the number of scale poles (e.g., unipolar or bipolar) was not completely resolved. Information was presented and discussed that the majority of responses (e.g., 80 percent or more) were of a unipolar nature. Specifically, the majority of responses to vibration were in an area of discomfort rather than comfort. The remaining responses (20 percent), providing a comfort type response, were obtained for vibrations above 15 Hz, which are usually not considered to be of crucial importance in ride quality research on vibration. Nonetheless, some members continued to perceive a bipolar scale as "more appropriate" than a unipolar type scale. The length of scale line was the last scale characteristic discussed in this section. The group agreed that the length of the scale was of no practical importance in either an applied or theoretical sense.

5.0 ADJECTIVES AND ADVERBS

A very large number of different adjectives have been used in various research studies. The use of different adjectives for scales (or scalar points) of the same physical characteristics (e.g., regarding polarity, type, and scalar points) was recognized as completely modifying the scale, scale values (particularly if also represented in numerical integers) and subsequent interpretation. Despite a diversity of opinions on different matters, there were several points of agreement within the workshop as follows:

The use of the word comfort or adjective variations as uncomfortable or discomfort appear to be the most appropriate for ride quality research. A note of caution is that words evoking a dichotomous sensation (e.g., comfortable vs. uncomfortable) should not be confused with words evoking a continuous sensation (e.g., discomfort).

Scale adjectives are often appropriately based on the goals of a project.

The scale adjective(s) should be used in subject instructions, and the same adjectives are optional on the actual scale.

The scale adjectives should remain constant across the scale.

Probably most important, a consensus was obtained that continued experimental investigation was needed for comparison of results obtained from different adjectives. Particular emphasis was placed upon the need for information regarding possible transformations that may exist between scales varying in physical characteristics or adjectives.

6.0 MAGNITUDE ESTIMATION PROCEDURES

Caution should be used in the application of these procedures. Prior to the use of magnitude estimation (or other ratio methods), several references (e.g., references 1-4) should be consulted for strength and limitations of the procedure in general. With respect to ride quality research, there are certain advantages and disadvantages as follows:

Advantages

There is no ceiling effect for responses as is typical of category scales.

A ratio procedure appears to be typical of the fashion in which many subjects express gradations in sensation.

There is a sounder basis for many statistical analyses than allowed for through the use of many category scales.

Disadvantages

Although a concrete example and instructions can be provided for a ratio idea, there is serious doubt as to whether the general population of people so often investigated have sufficient knowledge of a ratio concept to warrant this type of scaling.

Due to the fact that a realistic, stable, and meaningful standard has not been established for the operational environment, this type of procedure is questionable in field investigations. Dr. Kirby did relate some success with this procedure in a field investigation, but supported the restrictions of such a scale.

7.0 MULTIPLE RESPONSE MEASURES

There is a tremendous variation in the number and type (e.g., subjective measurement of noise, vibration, etc.) of sensation related responses obtained in different investigations (in addition to variation of responses obtained through the use of different scales). This variation has included single measures of one or more sensations (e.g., single trip experiences), as well as repeated measures of the same or different sensations. Despite discussion regarding appropriateness of each technique, which is often traceable to the objectives of a project, there were two general recommendations as follows:

> The number and kind of response measures obtained form the definitional basis of the criteria developed; caution should be exercised by a reader in determining appropriateness of fit between a specific criteria and his problem.
>
> Despite the logical basis for multiple measures (either of the same or different sensations) an investigation may place too great a demand upon a subject if the extent of multiple measures is not restricted.

8.0 RELATED TOPICS

As mentioned earlier, workshop time did not allow complete discussion of each scaling topic of interest. This section provides a resume of the remaining topics briefly discussed.

Behavioral models - Ride quality models were conceived of as extremely necessary for providing a framework for research programs, as well as a method for the integration of diverse information for the accurate prediction of subjective responses in this area. Ideally, such ride quality models should encompass provisions for vibratory and nonvibratory factors (e.g., seat characteristics, noise, temperature, etc.).

Multiple criteria - Initial discussions focused on the problem of whether composite criteria for noise and vibration (as well as other physical factors) or separate criteria (either hierarchical or successive in nature) need to be developed. Prior to solutions of such questions, it was decided that critical information was needed regarding a subject's ability to separate for a discomfort (comfort) response the influence of various physical factors (e.g., noise and vibration).

Intermodal information - Studies of ride quality should consider the importance of transportation between modes (e.g., between aircraft and train) in addition to those within a single mode.

Laboratory vs. field studies - A brief discussion centered on the comparison of these approaches (laboratory and field studies) with respect to experimental procedures, subjective scales, data analyses, and results. Larry Richards proposed that the two approaches are different and results not directly comparable. Other participants objected that the approaches are comparable, with experimental procedures, rating scales, etc., being more susceptible to error in field studies than

laboratory investigations, not less susceptible. Certainly, every effort should be made to use information from both approaches in modeling ride quality, with an emphasis upon obtaining and using the most appropriate measurement procedures within both field and laboratory studies.

Correlation/regression analyses - It was noted that correlation coefficients are often used to express the degree of relationship between subjective responses and physical variables (e.g., rms). However, when these correlations are based on the mean of subjective data (for a specific physical value) rather than data for each individual subject, the resultant correlation is higher than for the individual subject data case. Caution should be exercised in the interpretation of these higher correlation coefficients since they imply a higher degree of subjective response predictability than that which is actually the case for individual subjects.

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WORKING GROUP IV - RIDE CONTROL TECHNIQUES

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INTRODUCTION

This report represents a summary of the work that Group IV of the joint NASA/DOT 1975 Ride Quality Symposium accomplished during the two and a half days that it met at the Williamsburg Conference, August 13-15, 1975. The goal of the working group was to ascertain and document the state-of-the-art in ride quality control techniques for all of the primary modes of transportation and to point out the needs for the future.

Our working group was divided into six specialty areas according to the background and interests of the members. These areas and individuals were:

1. Aircraft Ride Control: J. R. McKenzie, W. E. Schoonover, R. C. O'Massey, and R. W. Stone.
2. Marine Vehicle Ride Control: P. J. Mantle.
3. Railcar Suspension Design: F. E. Dean.
4. Bus/Automobile, PRT Vehicle Suspension Design: R. Tarkir, A. J. Healey, and F. E. Dean.
5. Guideway Roughness Control: R. J. Ravera.
6. Tracked, Levitated Vehicle Suspension: L. M. Sweet and R. J. Ravera.

This group is primarily composed of systems design oriented engineers, from industry, government and universities. Therefore, most of the group have participated in engineering studies that include system design, analysis, hardware development, and full scale testing and evaluation. In particular, these system design and development projects have involved the evaluation of ride quality and in many cases, have required meeting contractual ride quality specifications.

BACKGROUND

In this work, ride quality relates to the level of vibration in the low frequency range up to 40 Hz or so imposed on the travelling public by either vehicular maneuvers or vehicular response to external environmental and on-board excitation sources.

Probably the single and most important reason why ride quality design is of interest lies in the increase in travel speed and consequent reduction of travel time allowed by smooth riding. The reduction of travel time is important in all public transport systems. Secondly, reductions in vehicular body vibration levels lead to longer life of structural components, which may or may not (depending on configuration) come at the expense of life of suspension components.

The process of initial design of a ride control system is illustrated in Figure 1, which indicates the three important ingredients present in establishing the ride quality environment. Firstly, guideway roughness characteristics need to be specified. Secondly, vehicle steering and suspension characteristics need to be identified and thirdly, the vehicle system response will be included to determine the environment. Expected knowledge of the environment can then be assessed in the light of available comfort specifications so that modification to the three ingredient characteristics can be assessed. Figure 1 shows that smoothing a rough guideway by imposing tight tolerances is a possibility.

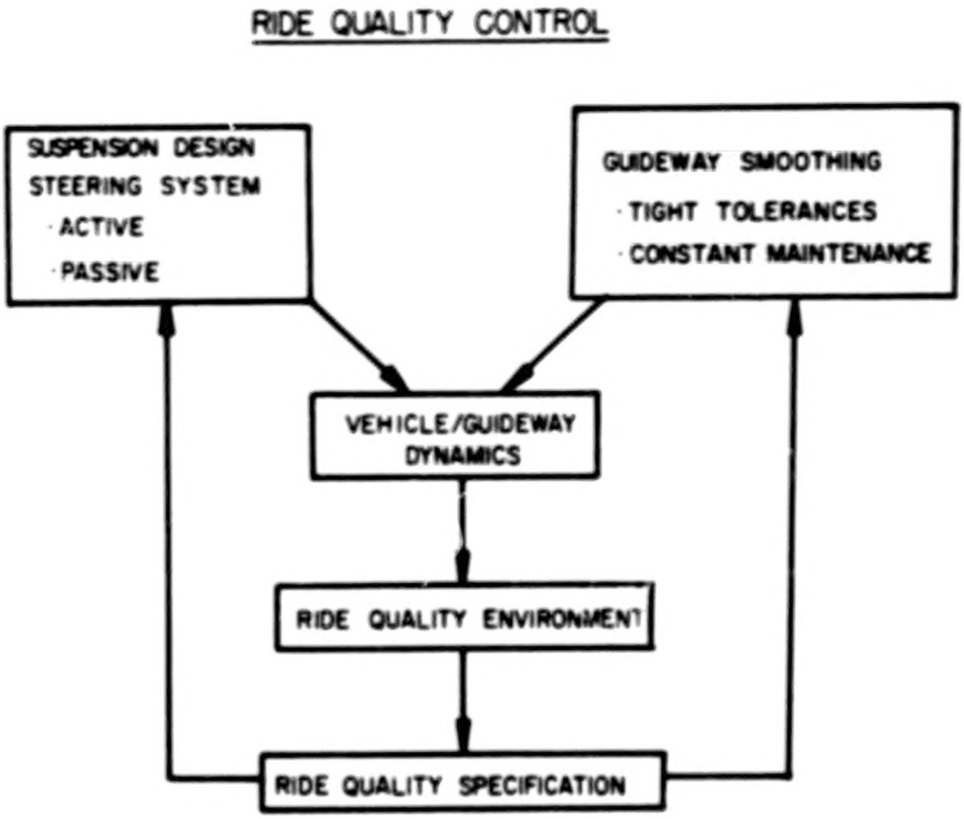

Figure 1. Ride Quality Design

The choice of active, powered, or passive steering and suspension system is also a design decision that must be assessed by the process of Figure 1.

For air and seaway based systems the process of initial design is not quite the same since modification of the weather is not possible. For air and seaway based transport the process is illustrated by Figure 2 in which reasonably accurate statistical models of the external excitation are used. This involves both probability distribution and spectra for atmospheric turbulence and seaway wave action.

OUTLINE OF REPORT

The purpose of this report is to:

1. Summarize techniques currently available to improve ride quality through vehicle, suspension, and/or guideway control. This includes air, marine, rail, bus, auto and advanced concept vehicles such as tracked levitated vehicles. State expected ride quality improvements by a systematic design procedure in terms of % change in ride quality, increased cost, increased component wear, weight, etc. List anticipated problem areas.

2. Discuss the impact of current ride quality standards on the design and verification process. In particular, attention will be paid to a desirable form in which to express the standard for each mode and exactly how the ride quality data should be taken and processed. Included in this discussion will be ideas on sensors, sensor location, filtering, and data processing techniques.

3. Finally, suggestions for the directions that future research should take both in the short and long term.

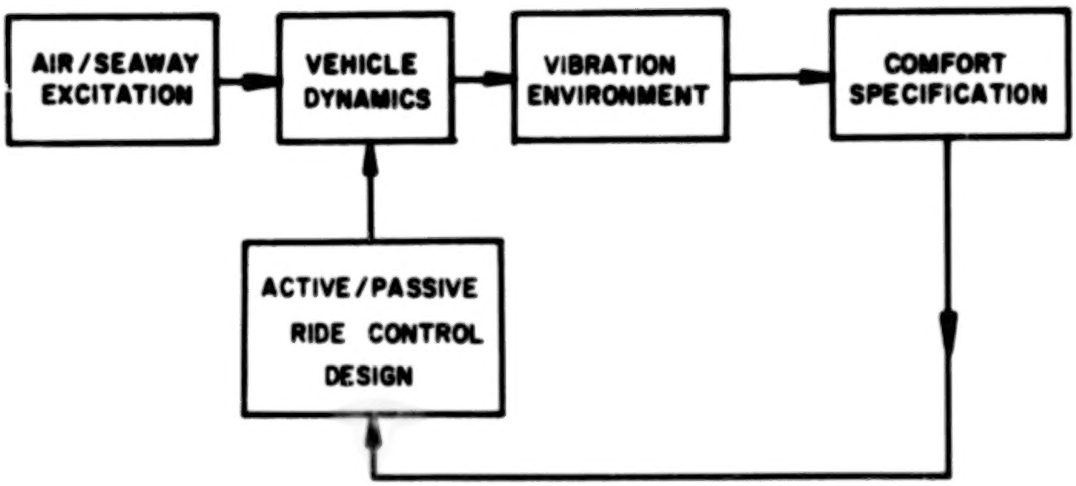

Figure 2. Air/Sea Based System Design

This report will be divided into four different areas. Firstly, the section of current practice in ride quality design will outline current procedure mode by mode. Secondly, the problem of the impact of ride quality specifications will be addressed. Thirdly, a section has been included which deals with the expected improvement by systematic design and use of ride control techniques and finally, some suggestions for further research will be given.

Throughout this report ride control methods considered will include upgrading the quality of the ground based guideway-rail or highway condition, suspension modification in terms of the fine tuning or adjustment of components, and advanced concepts using semi-passive or fully active automatic ride stabilizing systems.

CURRENT PRACTICE IN RIDE QUALITY DESIGN

Ride quality design procedures vary considerably between modes and while this report attempts to seek commonalities, nevertheless each mode is treated individually. First, air and seaway based system procedure will be discussed followed by the aspects relating to ground based systems.

Aircraft

Passive Methods

In the air based system, vehicle motion is controlled by pilot maneuvers. Limitations such as maximum desired bank or pitch angle must be observed. Low frequency vibration induced by atmospheric turbulence is controlled first by basic aircraft design methods such as

a) Maximize cruise wing loading;
b) Minimize empennage areas especially for powered light aircraft;
c) Analysis of flight dynamics (dutch roll, and short period characteristics and flexible mode shapes);
d) Reduction of strut bearing friction.

Active Control Methods

More recently in both commercial and military aircraft, applications of gust, maneuver and flutter alleviation systems using active control techniques is becoming state of the art. Active ride stabilizing control systems are also being developed along with fly-by-wire concepts and use of split and distributed control surfaces (split rudder, inboard and outboard ailerons, for example).(1)

The design procedure requires knowledge of the spectral density and probability descriptors of atmospheric turbulence that may be encountered on a given trip, as shown in Figure 3.

Vehicle dynamic response models then will allow a prediction of the aircraft response which can be evaluated in terms of a chosen comfort index. Usually, computer simulation is used and this provides the means for studies to be made concerning the benefit and cost trade-offs in flight controls.

Wind-Model

MIL-F-8785 specifies the form of the Von Karman gust spectral density to be used in design studies. The probability distribution is assumed to be the Gaussian normal form. This specification is based on safety considerations with the primary objective to retain minimal safe operation in any environment that the vehicle is likely to experience.

The curves shown in Figure 4, which illustrate the probabilities tabulated in Table 1, were established using the following relationship:

$$P(\sigma_g) = P_1 + P_2 - \int_0^{\sigma_g} \frac{P_1}{b_1}\sqrt{\frac{2}{\pi}}\, e\left(\frac{-\sigma_g^2}{2b_1^2}\right) d\,\sigma_g - \int_0^{\sigma_g} \frac{P_2}{b_2}\sqrt{\frac{2}{\pi}}\, e\left(\frac{-\sigma_g^2}{2b_2^2}\right) d\,\sigma_g$$

where

$P(\sigma_g)$ = cumulative probability that σ_g will equal or exceed a given level.

σ_g = root mean square value of gust velocity relative to the airplane body axis, ft/sec TAS.

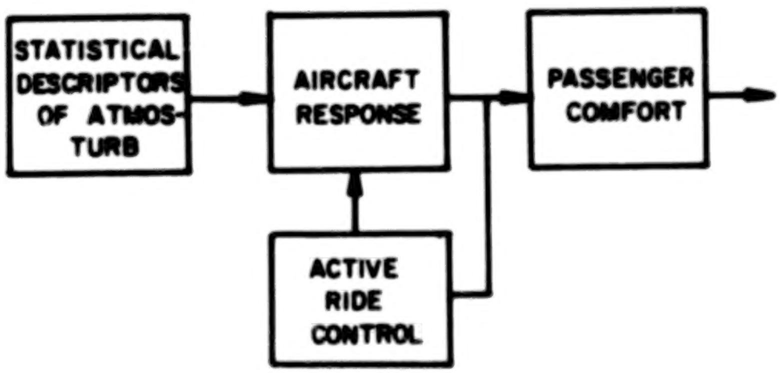

Figure 3. Aircraft Ride Control

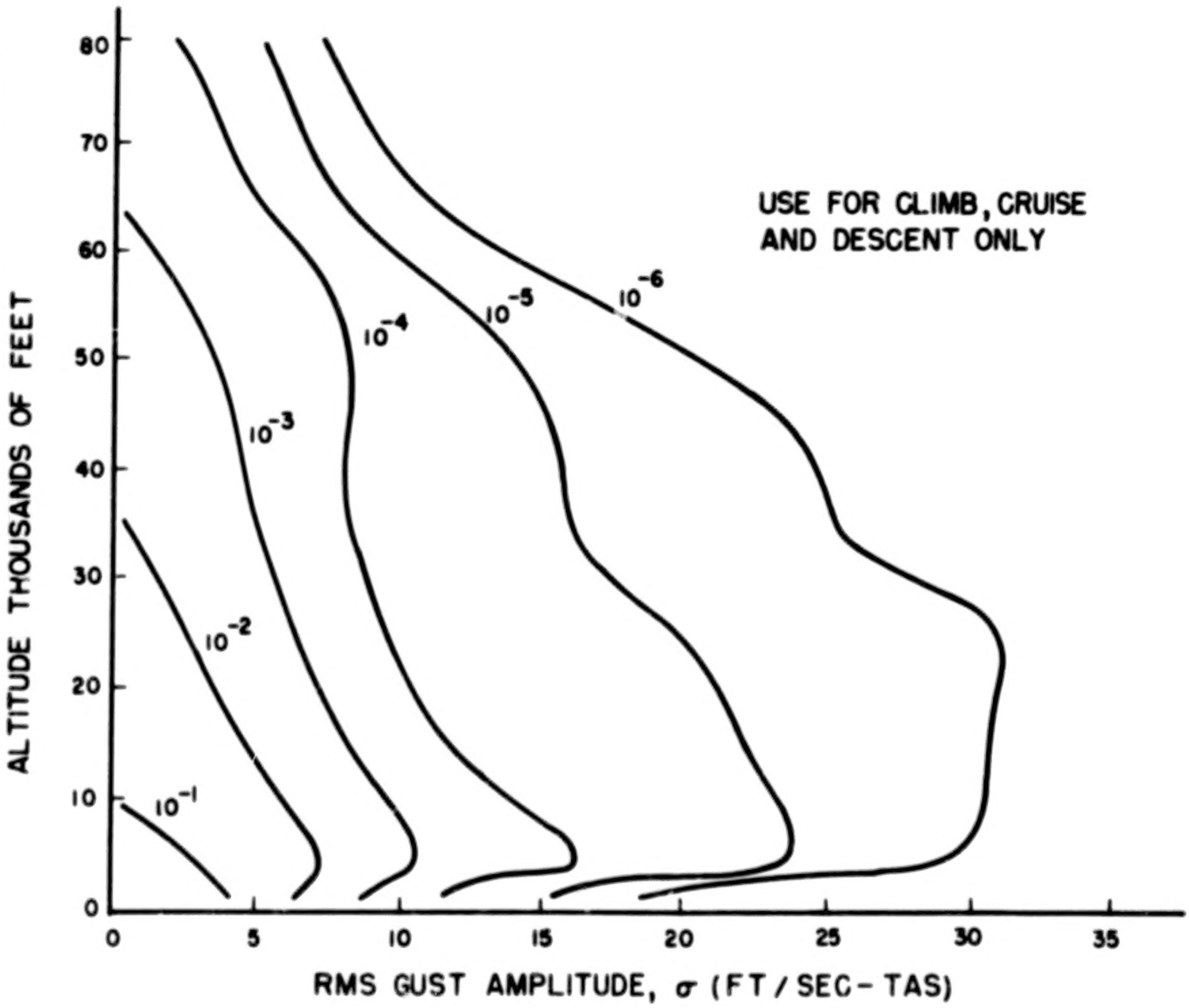

Figure 4. Exceedance Probability vs. Altitude and RMS Gust Amplitude

Table 1. RMS Gust Intensities for Selected Cumulative Exceedance Probabilities, FT/SEC TAS

FLIGHT SEGMENT	ALTITUDE (FT – AGL)	PROBABILITY OF EXCEEDANCE						
		2×10^{-1}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
TERRAIN FOLLOWING	UP TO 1000 (LATERAL)	4.0	5.1	8.0	10.2	12.1	14.0	23.1
	UP TO 1000 (VERTICAL)	3.5	4.4	7.0	8.9	10.5	12.1	17.5
NORMAL FLIGHT CLIMB CRUISE AND DESCENT	500	3.2	4.2	6.6	8.6	11.8	15.6	18.7
	1,750	2.2	3.6	6.9	9.6	13.0	17.6	21.5
	3,750	1.5	3.3	7.4	10.6	16.0	23.0	28.4
	7,500	0	1.6	6.7	10.1	15.1	23.6	30.2
	15,000	0	0	4.6	8.0	11.6	22.1	30.7
	25,000	0	0	2.7	6.6	9.7	20.0	31.0
	35,000	0	0	0.4	5.0	8.1	16.0	25.2
	45,000	0	0	0	4.2	8.2	15.1	23.1
	55,000	0	0	0	2.7	7.9	12.1	17.5
	65,000	0	0	0	0	4.9	7.9	10.7
	75,000	0	0	0	0	3.2	6.2	8.4
	OVER 80,000	0	0	0	0	2.1	5.1	7.2

P_1 = proportion of flight time spent in non-storm turbulence at a given altitude.

P_2 = proportion of flight time spent in storm turbulence at a given altitude.

and $\int_0^{\sigma_g} \frac{P_1}{b_1} \sqrt{\frac{2}{\pi}}\, e^{\left(\frac{-\sigma_g^2}{2b_1^2}\right)} d\,\sigma_g = 2P_1 \int_0^{\sigma_g} \frac{1}{b_1} \sqrt{\frac{1}{2\pi}}\, e^{\left(\frac{-\sigma_g^2}{2b_1^2}\right)} d\,\sigma_g.$

Values of P_1, P_2, b_1, and b_2 were taken from MIL-A-008861A. Table 1 lists values of RMS turbulence intensities for various exceedance probabilities, altitudes and flight segments.

The longitudinal wind component (in the direction of the mean wind) and vertical and lateral wind components are each represented by a gaussian process having a spectral density, $\Phi(\Omega)$, of:

$$\Phi(\Omega) = \sigma_i^2 \frac{2L_i}{\pi} \frac{1}{(1 + \Omega^2 L_i^2)}, \quad \left(\frac{FT}{SEC}\right)^2 / \frac{RAD}{FT}$$

where

σ_i = RMS turbulence level in an axis in feet/sec.

L_i = scale length in an axis, feet.

Ω = spatial frequency in radians/ft,

and the value for σ and L is defined in Table 2. Z = height above ground (feet).

Table 2. RMS Turbulence Level and Scale Length by Axis

	Vertical	Lateral	Longitudinal
σ	0.1 U	0.2 U	0.2 U
L	15 Ft for $Z \leq 30$ Ft .5 Z Ft for $30 \leq Z \leq 1000$	600 Ft 1000 Ft	600 Ft

With the external wind disturbance models above, the natural form for expressing the vehicle response is in terms of RMS acceleration.

Comfort Specification

The naturally desired form for comfort specification is in RMS acceleration terms. An allowance is made for a "human" sensitivity weighting function. Thus the Ride Discomfort Index is defined as:

$$D_i = \left[\int_{0.1}^{f_t} |W(f)|^2 |T_{cs}(f)|^2 \Phi_u(f)\,df \right]^{1/2} .$$

D_i = Ride Discomfort Index, (vertical or lateral).

$W(f)$ = acceleration weighting function, (vertical or lateral), 1/g.

$T_{cs}(f)$ = transmissibility, at crew station, g/ft/sec.

$\Phi_u(f)$ = Von Karman gust power spectral density of intensity specified in 3.1.2.12 and form specified in MIL-F-8785.

f = frequency, Hz.

f_t = truncation frequency (frequency beyond which aeroelastic responses are no longer significant in turbulence).

Acceleration weighting functions are defined for vertical and lateral acceleration by Figure 5. Table 1 lists probability of exceedance versus turbulence intensity.

With the Ride Smoothing Active Flight Controls, the following short term and applicable long term vertical or lateral axis ride discomfort index levels specified in Table 3 are used as a design guideline. The requirements apply, separately, to each of the vertical and lateral axes. For the lateral axis requirement only lateral gusts apply and for vertical acceleration only vertical gusts apply. Effects of attitude-hold or other pertinent modes are included where used.

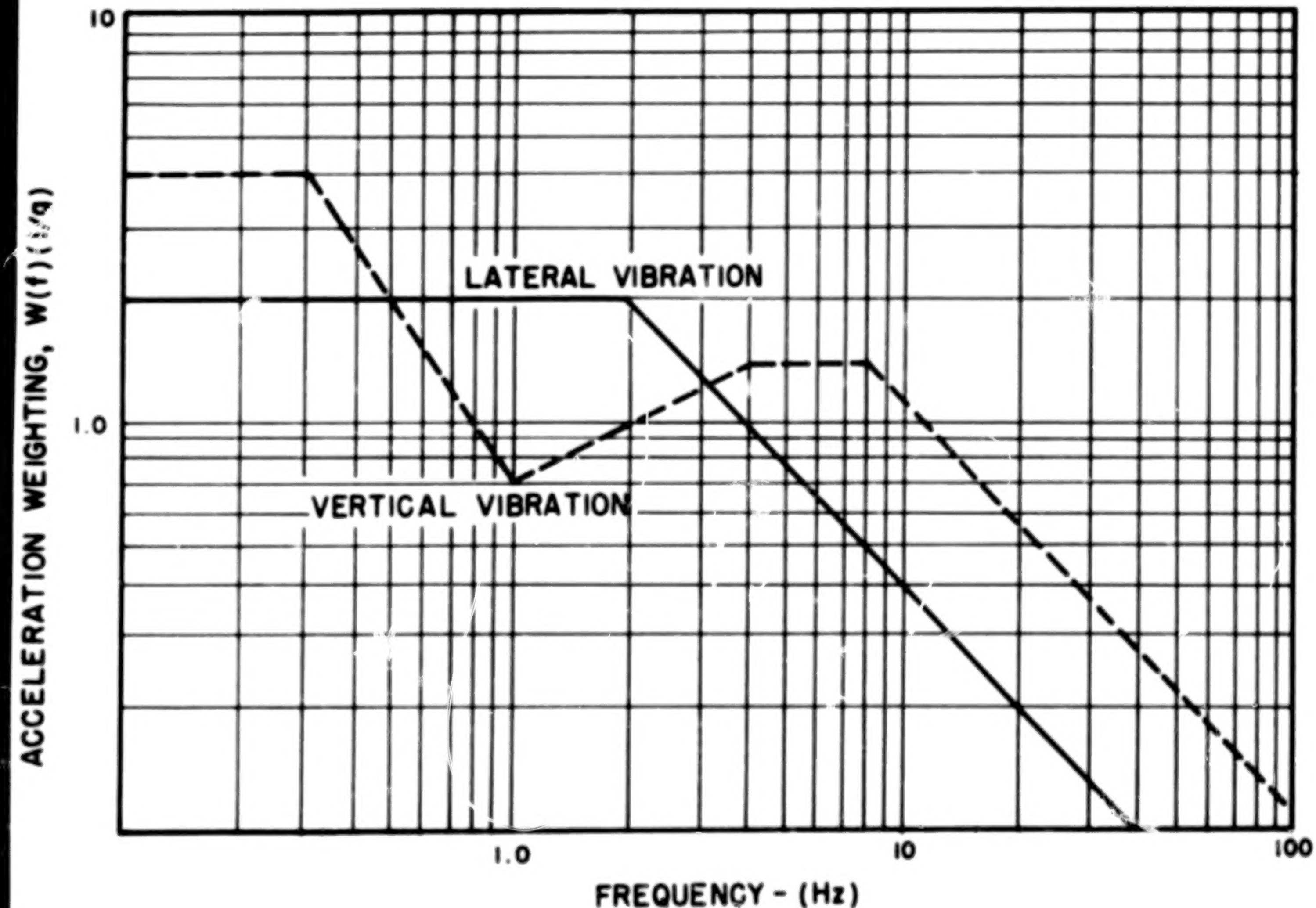

Figure 5. Acceleration Weighting Functions

Table 3. Ride Discomfort Index Limits

Ride Discomfort Index, D_I		Flight Phase Duration (Exposure Time)	Probability of Exceeding RMS Turbulence Intensity
Long Term Requirement	0.10	Over 3 Hours	0.20
	0.13	From 1.5 to 3 Hours	0.20
	0.20	From 0.5 to 1.5 Hours	0.20
Short Term Requirement	0.28	Less than 0.5 Hour	0.01

DISCUSSION

When used, ride smoothing systems are required to provide a degree of ride quality as defined by the Ride Discomfort Index. Ride requirements are stated in terms of probabilities, since the ride discomfort addressed by this requirement is generated by random turbulence. The exceedance probabilities and corresponding Ride Discomfort Index values specified are based on requirements that should provide ride quality equal to or better than that existing in currently operating aircraft within the USAF inventory.

The ride requirement for the basic aircraft, without a ride smoothing system, is included in MIL-A-8892. This requirement currently limits any single frequency vibration to 10.1 g, zero to peak, at frequencies below 22 Hz. This MIL-A-8892 requirement is currently being considered for revision within the AFFDL to include coverage similar to that included here. Consideration of multiple frequency aeroelastic responses and human sensitivity weighting factors is considered mandatory for evaluation of ride in turbulence.

There is disagreement in the literature on the proper approach for evaluating combined axis accelerations. Reference (2), the ISO standard, recommends that accelerations in separate

axes be considered separately; and Reference (3), a commercial aircraft study, recommended another method for combined axis acceleration evaluation.

Due to the general lack of agreement on method and limited test data available on combined axis accelerations, this requirement follows the ISO recommendation and places requirements only on vertical and lateral axis accelerations, separately. The reader should note that vertical ride discomfort is to be evaluated due to vertical axis turbulence only and lateral ride evaluated due to lateral turbulence only. No requirement is specified for roll gusts or longitudinal gusts, although for some STOL applications longitudinal gusts should be considered.

The turbulence intensities to be used are determined by the exceedance probabilities specified for Ride Discomfort Index. Generally, the system is required to reduce ride discomfort to the levels specified while flying in turbulence with a cumulative exceedance probability equal to or less than the probability specified. System nonlinearities must be considered. System deadzone and other nonlinearities must not be so large that ride discomfort exceeds the 0.10 or other pertinent long term limits in light turbulence. System saturation must not be so severe in turbulence at the 0.01 exceedance level that the 0.28 ride discomfort limit is exceeded. The reliability requirements for implementing a ride smoothing system are specified, in terms of mission accomplishment probability. The reader should note that cumulative exceedance probabilities for turbulence are stated in terms of stationary probabilities rather than the nonstationary probabilities used in reliability work.

Turbulence exceedance probabilities are tabulated in Table 1.

A stationary probability or cumulative probability of exceedance for turbulence encounter means that at a randomly

selected time during flight, the probability of being in turbulence at or above the stated intensity is of a given value. This does not define the probability of exceeding a given level of turbulence during a given flight or flight segment. On a fleet lifetime basis, this probability can be interpreted as the portion of total flight time to be spent above the stated intensity. Since the statistics upon which these probabilities are based were measured over extended operating times, the temptation to convert these values to hours/hour or hours per individual flight should be resisted.

The levels of ride discomfort specified are based on short term tolerance and long term tolerance. Data from Reference (4) indicates that below a Ride Discomfort Index of 0.07, little or no degradation in crew performance or passenger comfort is expected. Above a Ride Discomfort Index of 0.28 the USAF indicates that crew action must be initiated to reduce the acceleration environment by changing flight path, altitude and/or airspeed. Figure 6 illustrates unpublished data from a commercial airplane moving base simulator study by Boeing Company, Wichita, in terms of incremental pilot ratings (Cooper scale) due to accelerations which also indicate a limit near 0.28 for an incremental pilot rating of 3. (Note that a satisfactory rating of 3.5 in calm air plus an incremental rating of 3 in turbulence yields a total rating of 6.5.)

The only known production ride smoothing system designed to date, the B-1 system, used a vertical long term index near 0.10. The lateral B-1 requirement was more stringent. Commercial feasibility studies have used much more conservative design goals. Reference (5), for example, used an unweighted index of 0.03 in 0.01 turbulence. This is equivalent to an unweighted index of 0.015 in 0.20 turbulence at low level and is roughly a factor of 10 more stringent than the MIL-F-9490D criterion. The procuring activity, of course, may redefine the required values

NOTES: 1. UNPUBLISHED BOEING DATA FOR COMMERCIAL AIRPLANES
2. DATA OBTAINED FROM MOVING BASE SIMULATOR STUDY

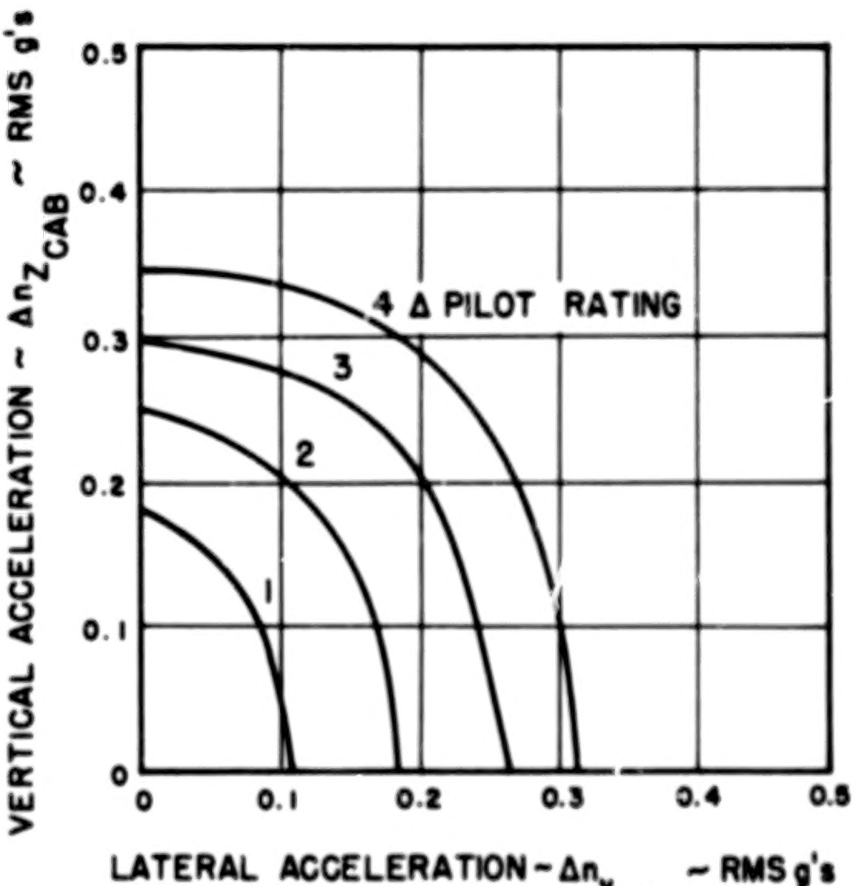

Figure 6. Effect of Combined Acceleration on Pilot Rating

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of the ride discomfort index to be used for specific procurements, based on unique mission requirements.

The B-52 is known for its marginal ride during low level penetrations. When compared to this long term criteria (3 hrs. = 0.10) the B-52 exceeds the criterion for medium and light gross weights and satisfies the criterion for heavier gross weights. Thus, for the initial penetration flight phase the B-52 ride is acceptable.

For later phases the ride is unacceptable, if the remaining low level flight phase exceeds three hours.

The Figure 5 acceleration weighting functions are based on the MIL-STD-1472 human sensitivity curves (2), extrapolated to less than 1 Hz. The extrapolations below 1.0 Hz, especially for lateral vibration, are supported by a minimum of data. However, the values defined represent the best current consensus of experts within the 6750th Aerospace Medical Research Laboratory and reflect the current U.S. recommendation to the International Organization for Standardization for human exposure to vibration from 0.1 to 1.0 Hertz. The weighting functions defined are truncated at 0.1 Hz and at high frequencies.

The reason for weighting function truncation is the limitations of the test equipment used to generate data upon which these curves are based. Moving base simulators can be used to simulate aircraft at low frequencies; however, the data obtained below 0.1 to 0.2 Hz is of questionable value since continuous oscillations at these frequencies do not normally occur in flight. In many cases, the pilot will control low frequency motions, effectively smoothing these oscillations and reducing the truncation error resulting from this approach.

Sea-Based Air Cushion and Hydrofoil Boats

The maritime history books are replete with descriptions of schemes to improve the seakeeping of ships. While not wishing to collapse the years of ingenious and hard efforts into a couple

of sentences, it is basically true that these schemes have not been too successful in the pitch and heave modes although quite successful in the roll mode. To quote typical examples of roll control used in conventional ships, these include shaping such as bilge keel and roll stabilizer fins. Some schemes include active roll fins that rotate, upon sensing a rolling motion, so as to provide a counteracting rolling moment. A typical 20-knot displacement ship underway in Sea State 6 beam seas might have a roll angle of up to 18-20 degrees but with application of the best of today's active roll control schemes, this can be reduced under the same conditions to 4-5 degrees resulting in a significant improvement.

It has generally been agreed, however, that if seakeeping is to be improved in head sea operation, then one has "to get the hull out of the water"--and that's where the hydrofoil and the air cushion craft come in.

Hydrofoil Ride Control

Passive System

The simplest form of ride control is manifested in the basic form of the surface-piercing foil as used on the Supramar and the Rodriguez hydrofoils. The foils, both bow and stern, have a basic V-shape* that pierce the surface. The area below the waterline provides the dynamic lift when underway to support 100 percent of the craft's weight. Stability comes from area stabilization, i.e., as the craft moves downward under some disturbing force, the area of the immersed V-foil increases, thereby providing the necessary upward force to counteract the downward motion.

This feature thus provides the basic stability to the surface piercing hydrofoil. In rough water, however, one can see that constantly changing wetted foil area occurs that gives rise to the acceleration levels felt by passengers and crew (and

*There are several geometric variants of this in operation, but it would not serve a purpose to digress and describe these--the principle remains the same.

cargo). In this case, due to the randomness of the waves and the high orbital velocities near the surface, this can induce both lateral and vertical accelerations that can be objectionable to a small percentage of those traveling. Some data are given later.

Active System

The fully-submerged foil, if submerged deep enough, requires some stabilization mechanism not inherent in the foil. A particular class of fully-submerged foil system that does not require auto-stabilization is the shallow submergence type used successfully on the bulk of USSR hydrofoils. The loss of lift as the foil approaches the surface is a self-stabilizing feature but this is clearly limited to relatively calm conditions. Hence, the main discussion here is restricted to the deep fully-submerged foil that has ocean-going capability.

Again, there are two forms of active control: one uses "incidence control" where the entire chord is rotated (about 1/4 chord) to change the lift force; the second uses "flap control" where just the flap is actuated and the main foil remains fixed. Both have their virtues but clearly the flap control method consumes less power than the incidence control method. As an example, the 65-ton TUCUMCARI uses 31 hp in its hydraulic actuation of the flaps, while the 68-ton FLAGSTAFF uses 105 hp for control by incidence.

The remaining discussion is restricted to the flap controlled, deep, fully-submerged hydrofoil. The ride control system is the same as the basic lift and stability system; i.e., the foils and flaps themselves.

Figure 7 shows a typical configuration of such a fully-submerged system.* While using slightly different geometries the system applies to such hydrofoils as TUCUMCARI, HIGH-POINT, JETFOIL and PHM. Trailing-edge flaps on each of the foils vary

*Insert to Figure 7 shows a surface-piercing foil for comparison.

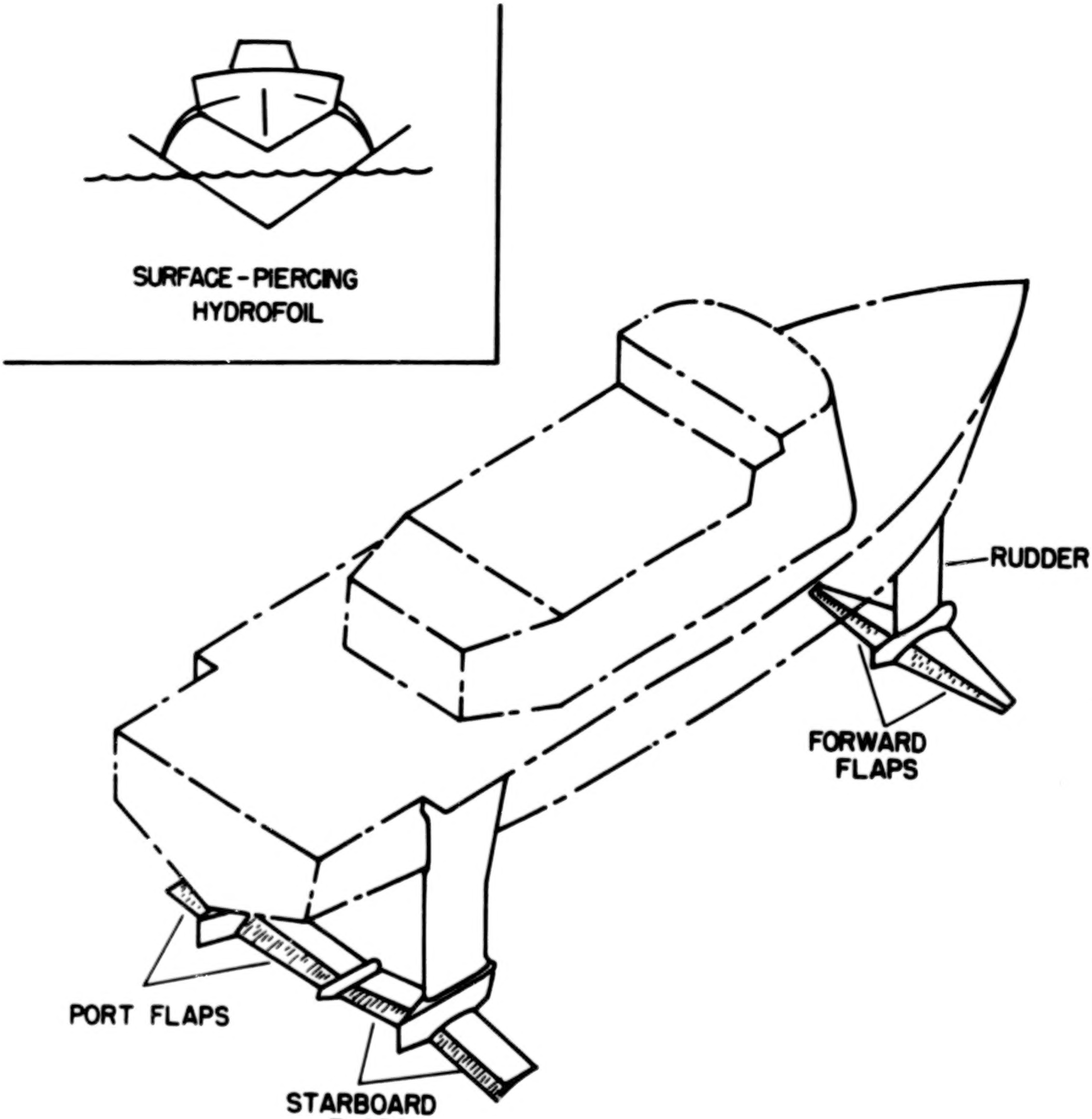


Figure 7. Fully-Submerged Hydrofoil
(Flap Control)

the foil lift as required for stability and control in response to signals from a 3-axis automatic control system. Rudder action also under automatic control for directional mode stabilization (with manual helm control for turning provided) is provided by swivelling the entire front foil-strut assembly. The trailing-edge flaps at the rear foils (port and starboard) can operate either in unison for pitch and heave control or differentially for roll control. Banked turns are incorporated to provide a better ride quality to the passengers and crew--nobody likes to make flat turns!

The height control is through a feedback of foil depth error. The height sensor is an ultra-sonic unit mounted in the bow. The feedback is oppositely phased to the forward and after flap controls. These control loops combine the functions of dynamic foil depth control and automatic pitch trim, without the necessity for trim integrators. The foil depth error to the after flaps is limited to assure that roll control capability is reserved under extreme rough water conditions. Pitch stabilization and damping are provided by shaping the signals from a single vertical gyro. Ride comfort in heavy seas is assured by a separate feedback to each flap servo from an associated heave accelerometer located over each foil.

Data from hydrofoils using such systems will be given later.

Air Cushion Craft Ride

Passive System

The current craft have used either a passive lift system or an active system using simple venting to atmosphere of the cushion. Figure 8 shows both these systems in simplified form. The passive system (Figure 8a) comprises a fairly conventional fan, either centrifugal or axial, that pressurizes air flow into the cushion. The hard structure is supported on this cushion. The height is determined by the depth of the flexible (skirt) structure suspended beneath the vehicle. The flexible

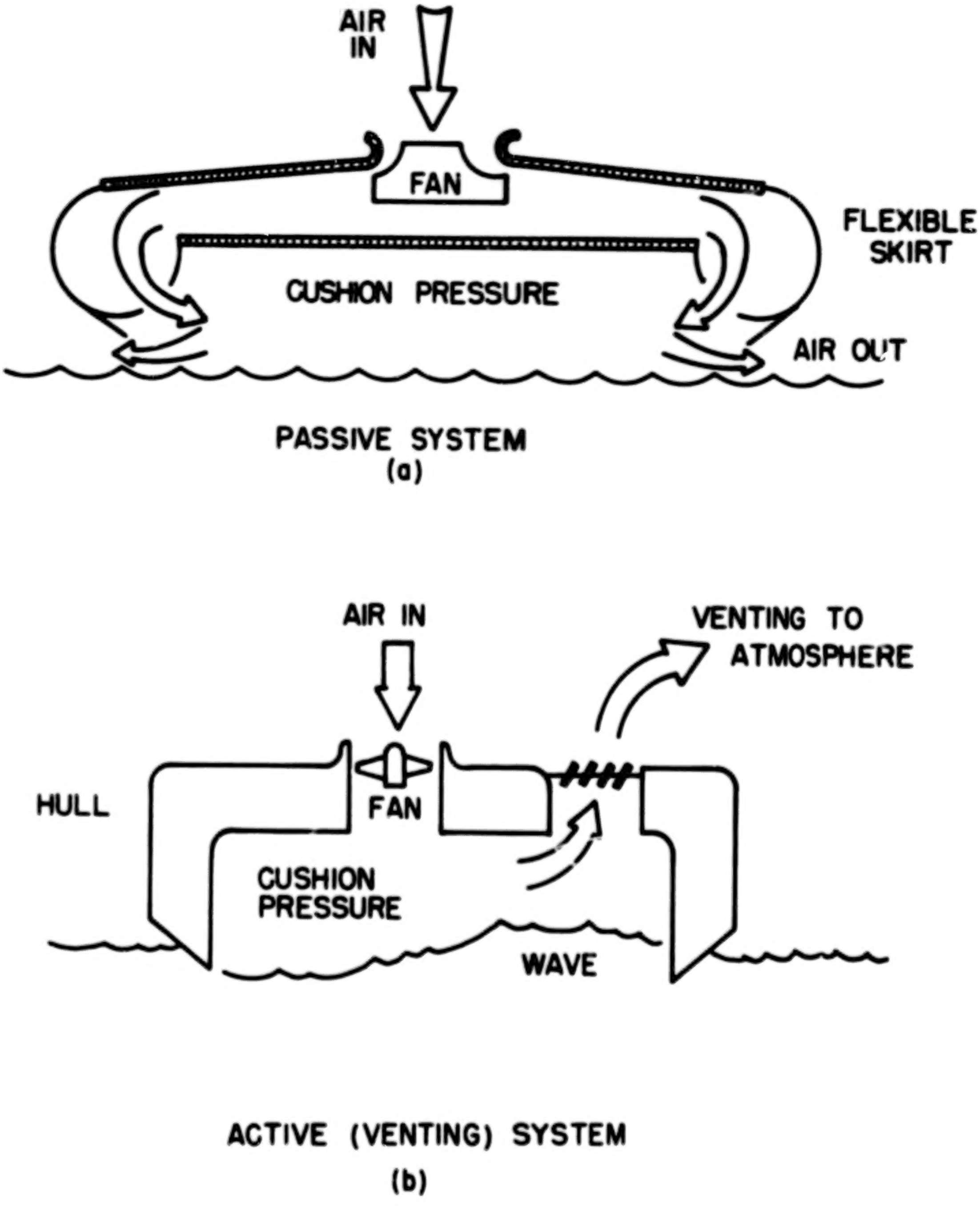


Figure 8. Passive and Active Lift Systems
on Air Cushion Craft

structure (usually rubberized control material) then flexes over the waves allowing (in the ideal world) the hard structure to platform the waves. Various skirt schemes are used and basic stability is assured in the simplest versions by compartmentation of the cushion giving rise to "pressure pads" that provide the necessary restoring moments.

Typical pressures in current craft range from 50-100 psfg. The forces acting on the vehicle in waves are predominantly due to "wave pumping" where the waves pump out the cushion of volume V causing pressure (p) fluctuations. The ratio of the pressure change (Δp) to the steady state pressure (p); i.e., $\frac{\Delta p}{p}$ is a direct measure of the vertical acceleration. For current craft with typical speeds 40-60 knots, the passive system gives unacceptable rides when operating in seas where the wave height is much above 50 percent of the cushion depth. Specific data will be given later.

Active System

All commercial craft use passive lift systems. Only two craft developed for the U.S. Navy, namely the SES-100A and the SES-100B, use active lift systems. Both these craft are of the sidehull form and both use simple venting of the cushion to control ride. The scheme is as shown in Figure 8b.

The basic scheme consists of an accelerometer forward of the c.g. that senses the acceleration level of the craft. A signal is then relayed to the vent valves located on the weather deck but connected directly to the cushion. As the wave pumps into the cushion decreasing the volume V and increasing the pressure p, the vent valves open and vent the cushion until the pressure falls to the steady state. A similar but opposite description applies for the downstroke or negative changes in pressure (acceleration). The vent valve thus continues to fluctuate, properly phased with the wave and acceleration forces to reduce the acceleration levels. The valves typically operate

up to 5 Hz and the data shows that from 50 percent to 300 percent reductions in acceleration levels are presently being achieved by this method. Unfortunately, rather large amounts of cushion air are dumped into the atmosphere at power levels up to 25-50 percent of the basic lift power. More specific data on ride improvement is shown later.

Current Ride Control Achievement

Now that the various current schemes have been described, some summary data is given to indicate the state-of-the-art in being able to control the ride of hydrofoils and air cushion craft. As might be surmised from the various papers presented at the symposium just prior to this workshop and from discussions during the workshop, there is not a clearly defined method of evaluating "ride quality." Three basic methods are currently in use in the hydrofil and air cushion craft community, all taking a slightly different view and giving information in certain forms depending on the needs of the user. For the moment, ride quality is being used synonymously with vertical motion. Discussions relative to lateral motion, noise, odor, temperature and psychological effects on ride quality are deferred to later.

In examining vertical motion, the predominant factor in seasickness at the lower frequencies (0.20 Hz - 0.60 Hz) and fatigue decreased proficiency at higher frequencies (say greater than 1.0 Hz), three forms of plotting data have been used. They are:

Method (a) - RMS g's versus Sea Roughness Parameter
Method (b) - RMS g's versus Encounter Frequency
Method (c) - Transfer Function versus Encounter Frequency

A short discussion follows on each together with some current data.

Sea Roughness Parameter (Method (a))

Frequently we speak of "how good is the ride in certain seas?" and data are often collected as RMS g levels in a sea that

is often only defined by its wave height. Hence, a Sea Roughness Parameter is defined as the ratio of the wave height to the height of the vehicle above it. One could better define the clearance height as the distance between some average (along the hull keel) lower point of the hard structure and some mean water level. It has been found convenient however for fast numbers to use the skirt height (h_s) in the case of air cushion craft and strut length (h_s) in the case of hydrofoils. The Sea Roughness Parameter (hw/h_s) thus expresses the size relationship of the vehicle to the sea over which it travels (defined by significant wave height--the most likely observed wave height). A value of $hw/h_s = 0$ would signify calm sea and a value of $hw/h_s = 1.0$ would signify cresting and onset of hard bottom contact.

An air cushion craft travelling in seas where $hw/h_s = 0.50$; i.e., waves up to 1/2 cushion depth, would experience RMS g's of the order of 0.40 g's (see Figure 9). With active ride control of the simple venting kind discussed, this can be reduced to 0.10 g's RMS approximately.

While a surface-piercing hydrofoil at a similar condition; i.e., $hw/h_s = 0.50$*, a similar acceleration level of 0.10 g's RMS is not unusual.

A fully-submerged foil at the same condition would have an acceleration level of approximately 0.04 g's.

Most of the data plotted in Figure 9 applies to craft in the 40-60 knot speed region and over craft sizes 10 to 300 tons.

Clearly, frequency of encounter is of prime importance and data are also collected by Method (b).

RMS g's and Encounter Frequency (Method (b))

Another method of collecting data has the format familiar to the user of the ISO curves. Here the data are

*Some interpretations are needed to account for immersion depth of foils.

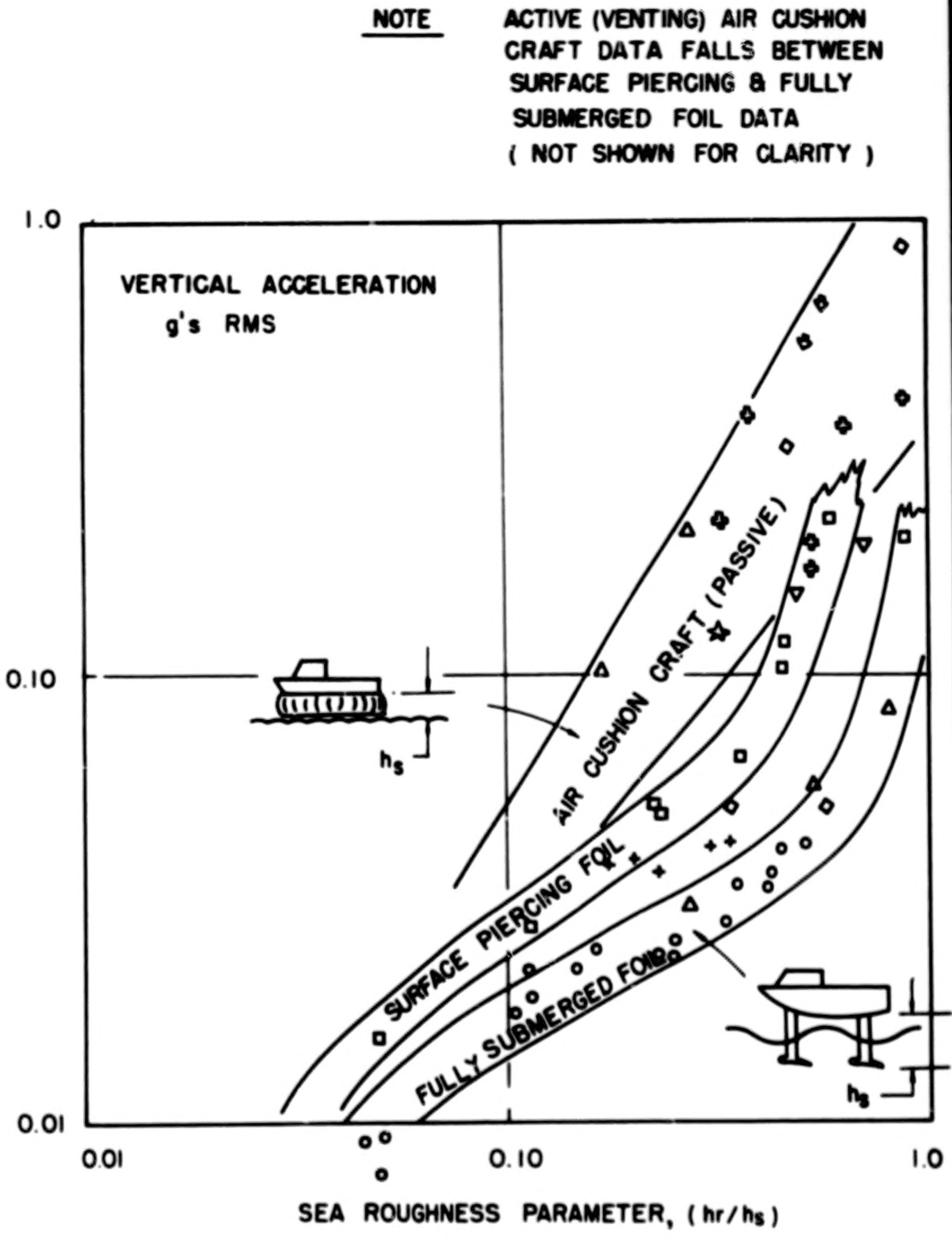


Figure 9. Ride Quality of Cushions and Foils

collected in terms of g's RMS plotted against the standard center frequency of 1/3 octave. The selection of 1/3 octave bandwidth is fairly arbitrary and is done for two reasons: one, some limit must be selected to standardize the bandwidth; and two, a 1/3 octave has some meaning on the noise spectrum! With this sound reasoning (!), typical data are shown in Figure 10 for fully-submerged hydrofoils and in Figure 11 for one of the two sidehull air cushion craft both with and without ride control active. The data in Figure 11 apply to test data collected at 30 knots in Sea State 2. Note that at the frequency of peak acceleration value ($\omega_e \sim 1.5$), the reduction due to ride control is of the order of 65 percent.

Transfer Function (Method (c))

The third method of data collection attempts to bring in the amplitude dependency on frequency of random seas. The transfer function expresses the ratio of the acceleration level (a) incurred to the wave amplitude (A) which is in itself a function of the encounter frequency (ω_e). If the vehicle exactly followed the waves and they were sinusoidal in nature, then $a/A = \omega^2$. A compilation of three representative craft expressed in this format is shown in Figure 12. Note that up to certain values of encounter frequency, wave following is evident. Very little data are available in this form although it offers the most promise in treating in exact form motion over random seas of noncharacteristic frequency. This method will be referred to again later when discussing future developments.

Some Trade-Off Considerations

Two basic requirements have brought the advanced marine vehicle into being: (1) the need to increase speed over water, i.e., faster than conventional 15-20 knot displacement ships; and (2) the need to achieve "good" seakeeping and ride quality while attaining the high speeds of 50-80 knots. Obviously, the two requirements are related. It is not intended here to discuss the trade-off between travelling slower to improve ride quality.

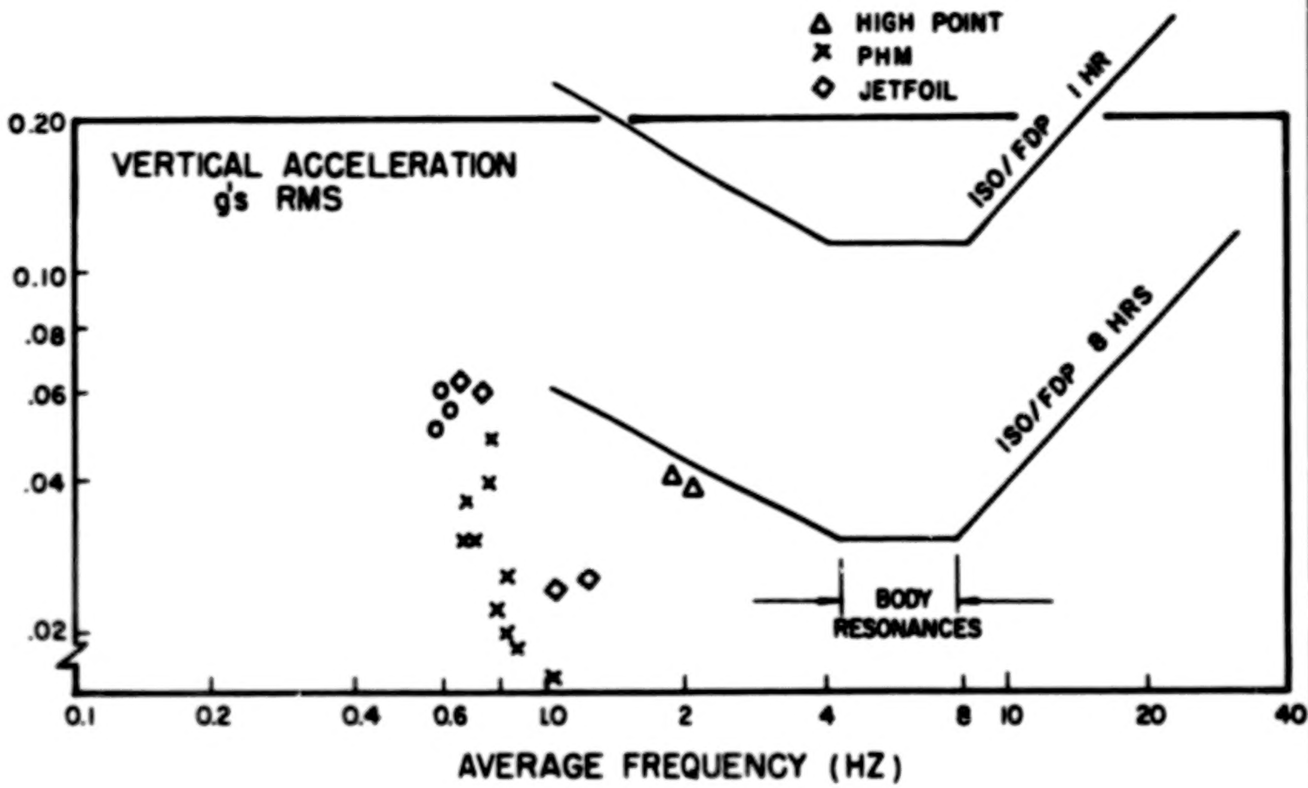


Figure 10. Ride Quality of Fully-Submerged Hydrofoil (Method b)

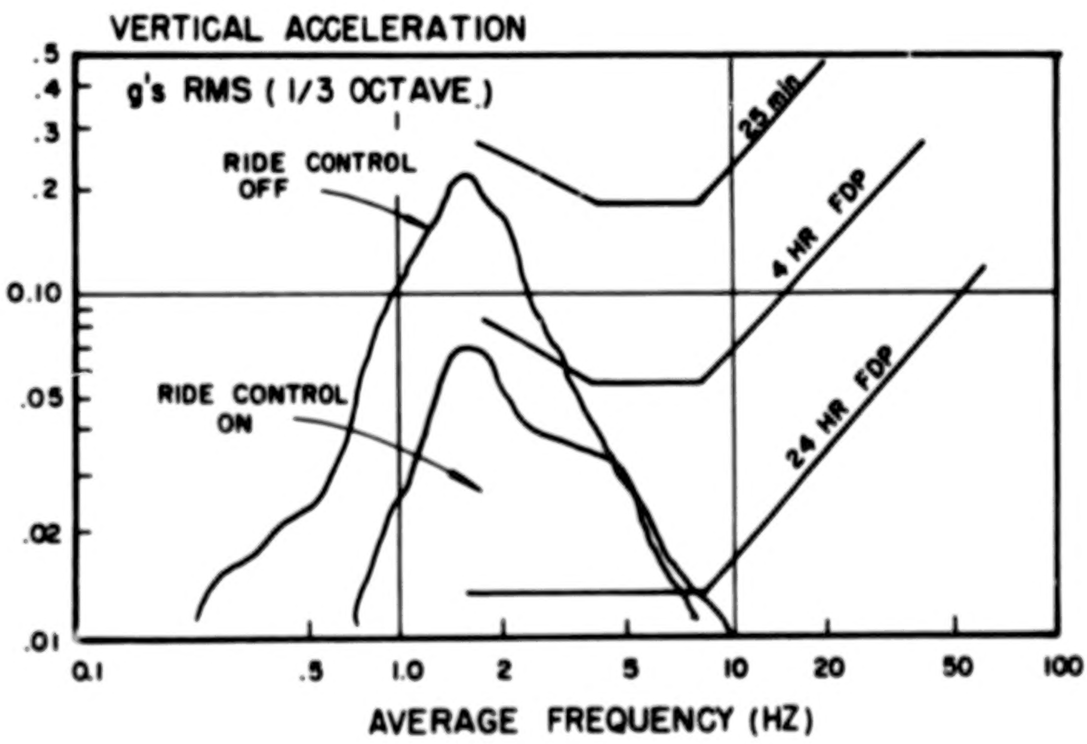


Figure 11. Ride Quality of Typical Air Cushion Craft

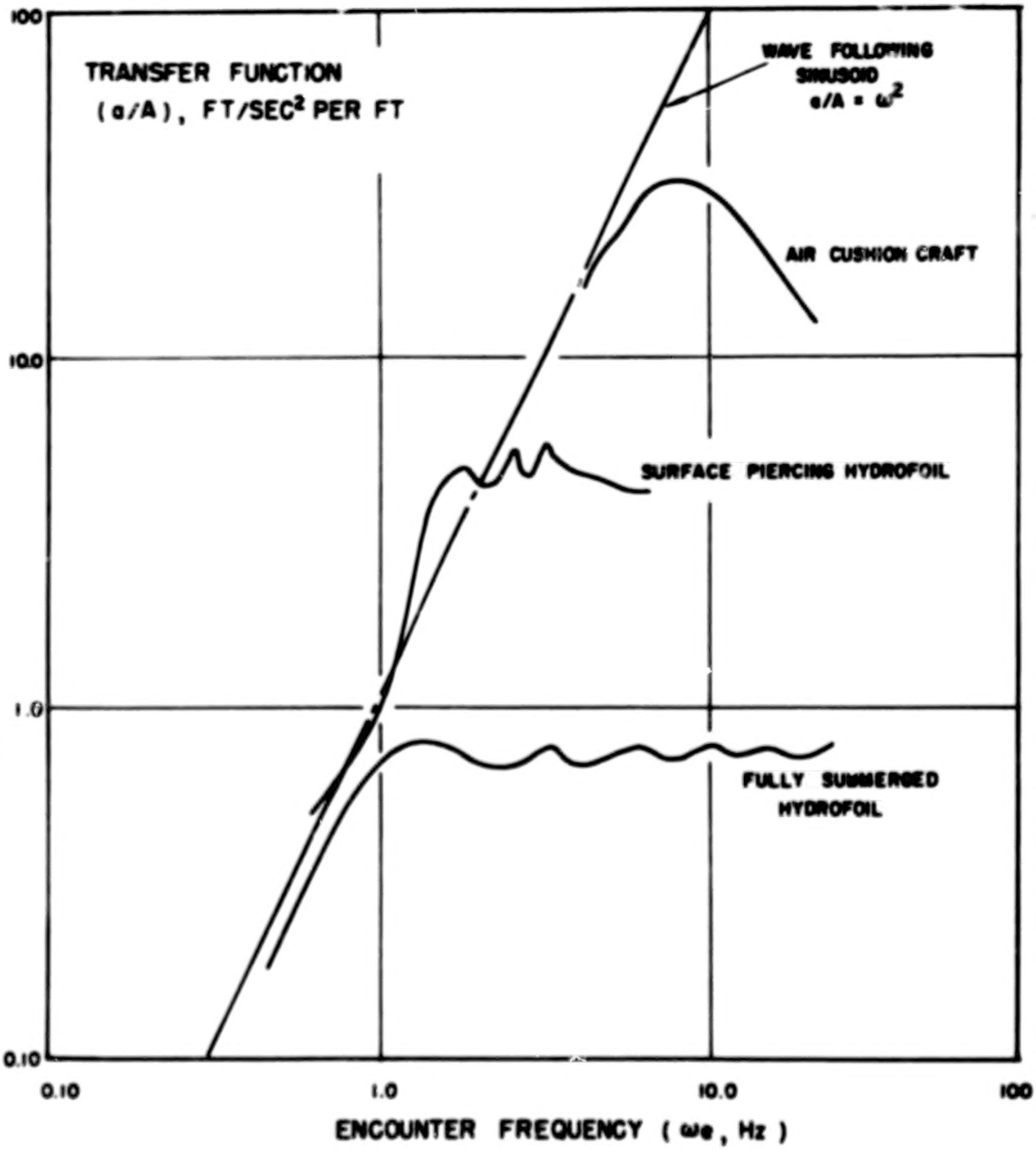


Figure 12. Transfer Function of Cushions and Foils

It is taken that U.S. Navy military mission analyses and commercial interests economic analyses have established the need to go fast. So it is taken here that speed is fixed; now what are the trades to achieve ride quality within some definable limits while travelling at these speeds?

First, the buyer has the choice between vehicle types; e.g., a fully-submerged hydrofoil has a better ride than a passive lift system air cushion craft. Second, given a vehicle he can choose between choices of ride control schemes; e.g., the choice between flap control or incidence control or fully-submerged hydrofoils.

Thirdly, the buyer can choose on the basis of cost, again between vehicles or between configurations of a particular vehicle. A brief summary follows on some of these considerations.

Technical Trades

Consider first the air cushion craft. The following list provides some comments on this type.

(a) A deeper cushion will reduce pressure fluctuations by a given wave. Hence, paying the penalty of more weight of deeper skirts and stretching of the state-of-the-art of skirt technology could do this. Current designs are at upper limits of skirt depth where $h_s/B \approx 0.15 - 0.20$ where B is cushion beam.

(b) Addition of more lift power (and lift flow) instead of providing active lift systems. Approximately 25 percent more flow would achieve 50-100 percent better ride.

(c) Addition of larger number of fans to effectively change stiffness of cushion. This implies increased weight, more components and reduced reliability, etc.

(d) Choice of active fans instead of wasteful energy vent valves. This is under development by U.S. Navy and looks promising based on test data (model scale) but is unproven.

For the hydrofoil, some trades include:

(a) Use of flap control versus incidence control. The hydraulic power for the flap control TUCUMCARI is 31 hp and for the incidence control FLAGSTAFF is 105 hp. While this is worth considering, the power requirements are quite small. For example, up to 1500 tons, control requirements do not exceed 1500 hp. So we are talking 1-2 hp/ton for ride control (integrated with the basic lift mechanism).

(b) Use shallow draft foils and rely on surface effect to control ride. The trade here is complexity of electronics versus low sea state capability. As will be given later, the cost of electronics is not large and the sea state is usually dictated by mission. The USSR hydrofoil is mainly operating in the many rivers in USSR. Thus this trade is an available option for them.

(c) Use surface piercing versus fully-submerged. Here again simplicity and cost are traded against ride quality. Figure 9 shows a 2 or 3:1 gain in ride quality of a fully-submerged over a surface piercing. Is the buyer/operator willing to pay 2 or 3:1 in price to get this?

(d) A good rule is that the strut length is equal to the significant wave height. Struts are heavy and expensive and rob from payload. Hence, short struts (and lower sea state capability) versus cost is another trade. This option has been exercised on JETFOIL; for example, long struts on the Hawaii boat because of the rough seas there versus short struts on the Hong Kong boats because of sheltered water operation.

Other trades that every designer must contend with are engines (diesel or gas turbine) to achieve the high speeds required, etc., etc., but these are not considered here since

they do not directly influence ride control but do affect the speed performance of the craft.

Ground Transport Vehicles and Systems

Ground transportation vehicles can be divided into two classes, rail vehicles and automotive vehicles, depending on the method of guidance.

In a general sense, ground transport vehicles lag behind aircraft and hydrofoil boats in the development of objective design methodology for ride control. In the past, ride control has been accomplished largely by subjective evaluation and empirical techniques to specify suspension system components based on assumed rail and road quality. Control of rail and road quality both for initial construction and later maintenance are usually treated separately from vehicle considerations. In some respects this has been the case because track and highways are required to service a variety of vehicle types.

Railcar Suspension Design

With railroad vehicles, ride quality control is currently achieved using front and rear trucks which form a primary isolation system on top of which the car is supported by a secondary suspension. Current design practice allows for vertical and lateral restraint in the secondary suspension with friction and stiffness dampers to control rock-roll motions. Use of rubber bushings serve to isolate higher frequencies in the "noise" range while the mechanical or air-bag springs and friction dampers serve to isolate the car against lower frequency ride vibrations.

The design procedures employed have been largely empirical until recently. Advances in computer modeling have now led to vehicle simulation prior to specification of suspension systems parameters. Using this procedure requires, as with air and sea craft, a spectral density representation of the exciting inputs

and a ride quality criterion that allows evaluation of an acceleration spectral density for all six degrees of motion. Such a criterion and design procedure are not currently available.

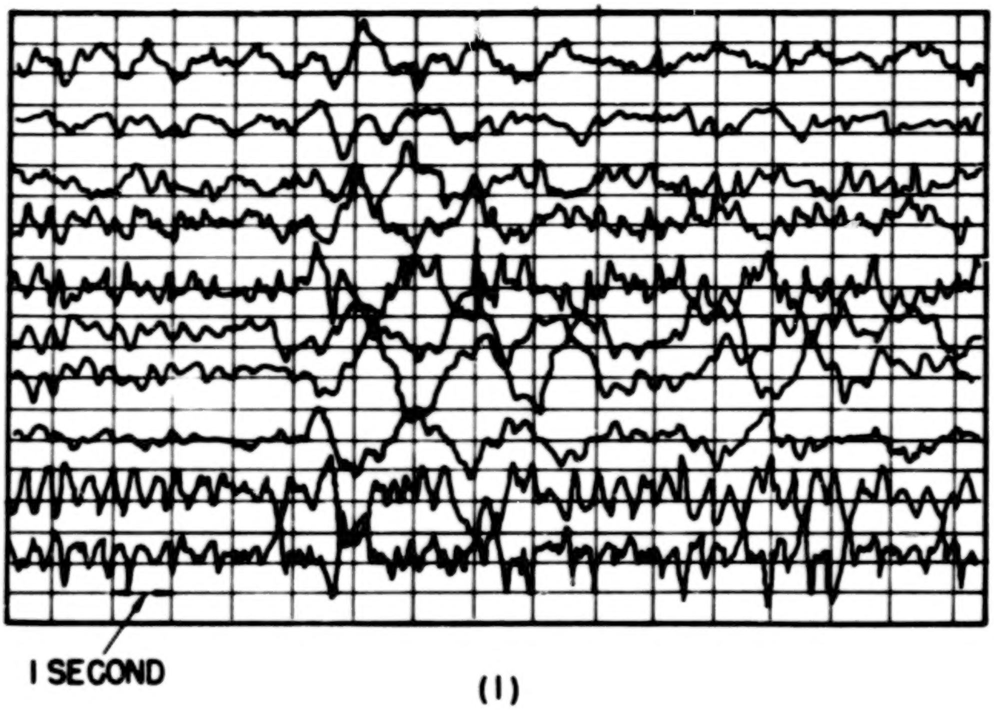
In practice, the recognized need for better track maintenance is finally underway, with recent funding to upgrade the Penn Central Track between Washington and New York and with the decision by U.S.R.A. to make it an exclusive passenger line. The possibilities for improved ride are indeed quite dramatic as can be seen in Figure 13, which shows comparative suspension element performance on poorly maintained bolted rail versus somewhat better maintained welded rail. Both cases are from the same track.

It should be emphasized that ride improvement alone exerts very little demand for new forms of track construction or for expensive realignment of right-of-way. Merely proper maintenance of conventional construction offers vast room for improvement. Research into track construction/maintenance should therefore be primarily directed at finding more efficient means of building and maintaining the existing standards of top quality track. This will suffice for the operation of passenger trains up to 130 MPH. Further extension of the speed range will require radically higher investments in both vehicles and in track construction techniques.

Systematic considerations in the design of suspension systems include:

(a) Assurance against hunting instability (6);

(b) Design for better resistance to rock-roll motions. In this regard, the length of track sections must be varied so that the kinematic resonance due to superelevation variation at the roll natural frequency does not arise;



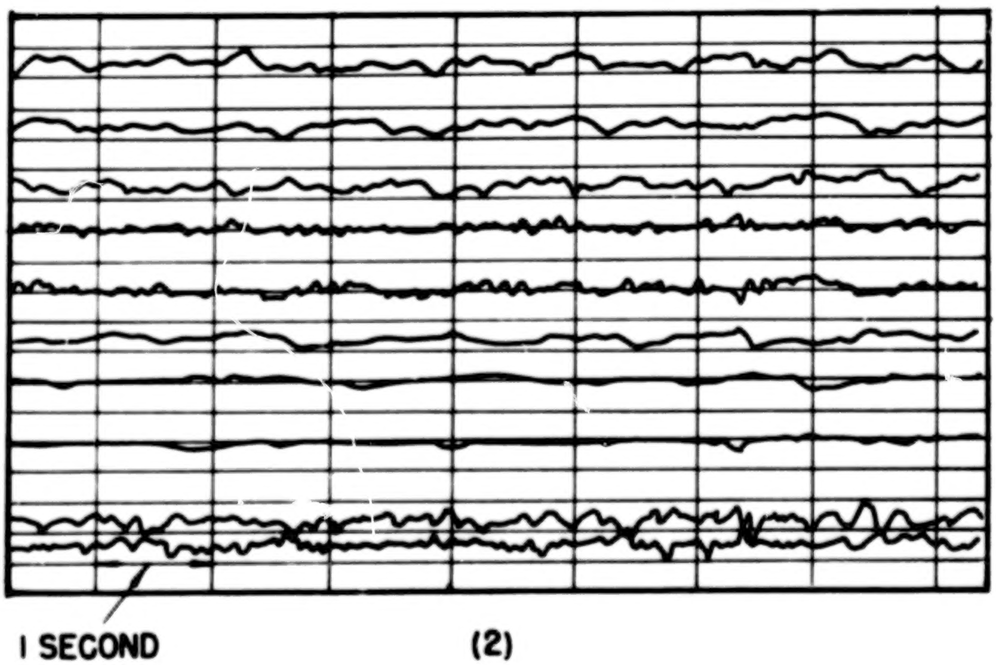


Figure 13. Effect of Track Quality on a Representative Sample of Suspension Element Strokes and Forces
(1) Run 36, Test 2 - 70 MPH - Poor Quality Track
(2) Run 36, Test 5 - 90 MPH - Good Quality Track

(c) Assurance that body bending and torsional modes do not coincide with dominant excitation frequencies from track elevation irregularities and track motion.

Current performances of Metroliner cars on poor and good quality track at medium speed are illustrated in Figure 14. Typically, a good ride would be characterized by vibration levels less than 0.05 g. The secondary suspension stiffness is often adjusted to make the first body resonance frequency around 1 Hz. Lower frequencies yield better ride but require larger stroke from the suspension components. Figure 14 illustrates that the primary lateral vibrational energy is contained in the 1 Hz, 2.5 Hz and 8 Hz components for revenue Metroliner cars.

Automotive Vehicles

The primary difference between railroad and automotive vehicles is in the lateral guidance. Steered most commonly by rubber tires, automotive vehicles rely heavily on the isolation characteristics of rubber tires as the primary suspension element and on coil, or leaf or torsion bar springs in combination with shock absorbers to provide secondary suspension for ride control. Steering is accomplished by turning the wheels, which generates a slip angle at the road-tire contact zone and, due to the nature of the tire, a lateral force develops in the carcass of the tire reacting to turn the vehicle.

Leaf springs, being made up of layers of several flat strips clamped together, exhibit a large amount of friction and are generally stiff in the lateral direction. Coil springs, on the other hand, are weak in the lateral direction. For these reasons, coil springs, with wishbone-type linkages, are usually employed in automobile front-end suspensions and leaf springs, suspending the body over a rigid axle, are employed in the rear.

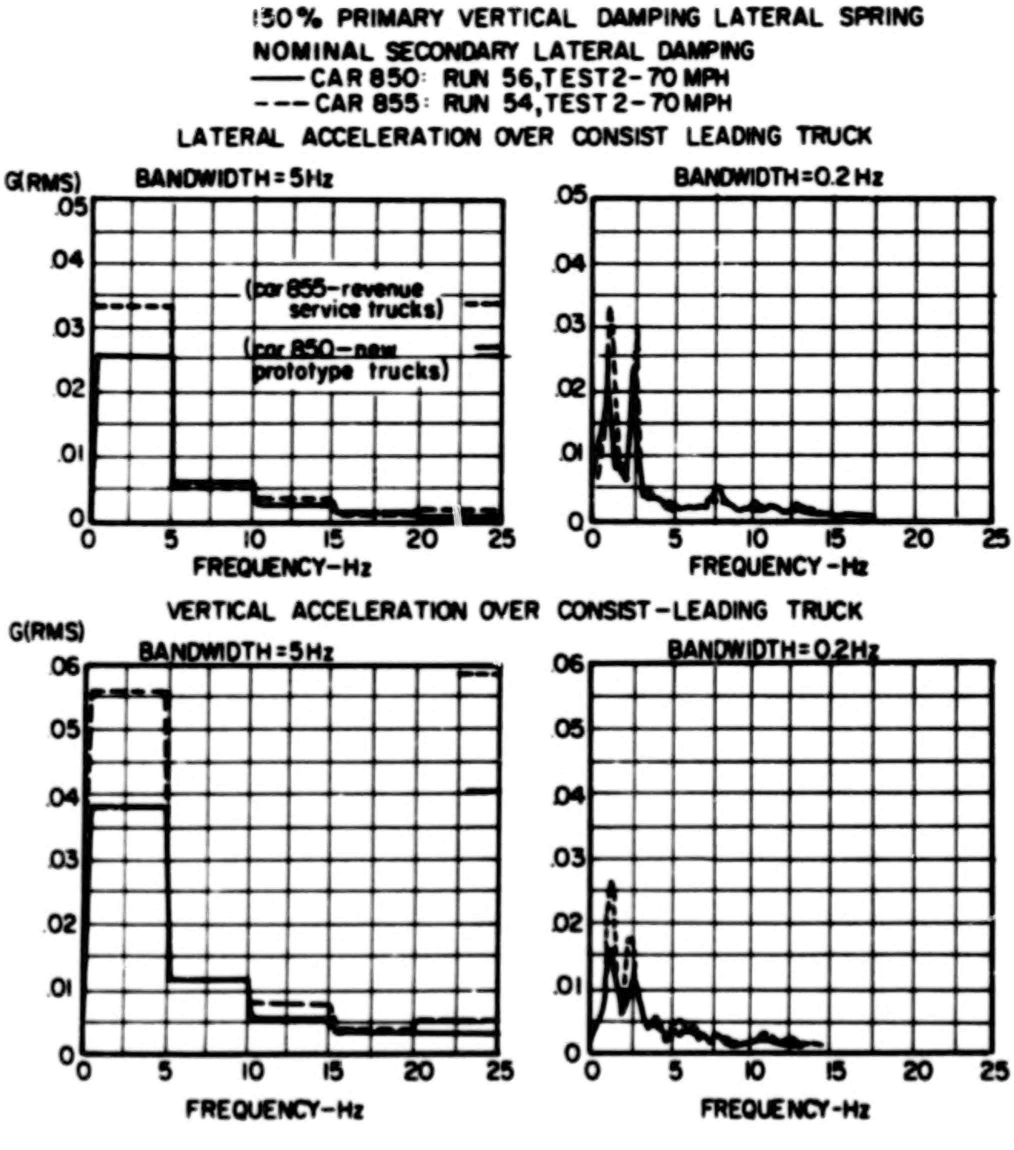


Figure 14. Comparative Acceleration for the Two Running Test Cars (Taken from (6).)

The coil spring and wishbone employed with independent suspensions provide better ride control than a rigid axle, because of the significant amount of vibrational energy transmitted to the body from the axle roll mode. However, because of cost considerations, most automobiles are made with rigid rear axles and only expensive sports cars have all four wheels independently sprung. Ride is generally improved when the suspension stiffness is lowered, whereas roll and road handling are generally impaired. The addition of torsion-bar roll stiffeners either front and/or rear helps to minimize roll in the curves, while leaving body bounce and pitch modes unaffected. Shock absorbers are included to damp body and wheel bouncing and to minimize tire forces.

The current design methods include computer simulation of the vehicle dynamic response to various roadway inputs, including smooth bumps, ruts and general random roughness. While rough guidelines indicate that the primary vehicle bounce mode should occur around 1 Hz with a stiffness and damping distribution (front/rear) to be roughly in proportion to the load distribution, final designs are always built, tested and evaluated experimentally. Objective ride quality evaluations are performed. A high degree of sophistication exists in vibration testing, for example. However, the lack of a well-accepted design criterion for ride quality, based on all possible maneuvers the vehicle is likely to undergo, seems to have led to ratings of relative ride between new and existing designs as the test for acceptability.

For vehicles with more than two axles, such as busses and trucks, rigid-beam-type axles are usually used with leaf or air-bag springs as secondary suspension elements. The air-bag spring has the advantage of good high-frequency noise isolation characteristics. The use of rear-axle leaf springs with their high friction eliminates the need for rear shock absorbers and thus reduces maintenance costs.

An example of the latest state-of-the-art design for busses is given by three prototype Transbusses (7).

The American Motors General Transbus uses a fully independent front suspension design using unequal short upper and long wishbone-shaped lower control arms. Both control arms are cast of high-strength steel with the steering knuckle supported by ball joints. The lower control arm is pivoted on rubber torsilastic suspension members. The rear suspension is similar to the front, in that two torsilastic springs support each wheel and the height is controlled by a hydraulic cylinder acting on one of these springs. One shock absorber is used at each wheel. The tandem rear axles are of rigid-beam-type design integral with the differential drive gearing. The axles are located longitudinally by four strut rods each and a solid link connects the axles to the torsilastic springs. The suspension position relative to the body is sensed at both front corners and at the rear. Tires are low profile cantilevered size T50C-19.5.

The General Motors Transbus prototype incorporates a fully independent front suspension design using unequal short upper and long wishbone-shaped lower control arms. The upper control arm is a two-piece steel casting, and the lower control arm is fabricated of sheet steel. The steering knuckle pivots on a kingpin supported in the upper and lower control arms. The tandem rear suspension design is of the deDion type where each rear wheel is mounted to an aluminum air spring beam with an air spring located at each end. Each air spring beam on the common axle is located by two strut rods and a deDion tube. One shock absorber is used for each wheel. Leveling values at each front and rear wheel adjust the pressure in the air springs to control the coach height. Tires are of low profile cantilevered design, size J50C-16.5, optional size J50C-19.5.

The Rohr Transbus prototype incorporates a tandem, fully independent front suspension design using automotive-type unequal

short upper, and long lower control arms supported by strut rods. The upper control arm is made of steel, and the lower control arm is a high-strength steel casting. The strut rod and lower control arm combine to carry longitudinal loads. The suspension is sprung by an air-bag spring acting on the lower control arms. The steering knuckles are attached by ball joints, and a single shock absorber is used at each wheel. The tandem rear suspension design is of the deDion type where each wheel is mounted to a large, combination bolted cast steel/fabricated aluminum trailing arms. These arms are attached side to side by the deDion tube. Transverse loads are carried by a rod on each deDion tube. The brakes and wheel bearings are carried in the trailing arms, which also carry the air-bag springs and the shock absorbers. The bus is leveled by adjusting the air pressure in the air spring bags. Leveling values at the front corners and at the rear directly control the flow of air in or out of the spring bags. Tires are mounted dual tandem and are of the low-profile cantilevered design, size MR60-16.5

All three Transbus vehicle designs have a seat design in which the transverse seats are cantilevered from the bus sidewall. All have a moderately high level of plushness and comfort.

The three resulting Transbus prototypes, using carefully chosen materials and engineering design techniques, have demonstrated that the ride quality of the conventional bus can be greatly improved. A.M. General Corp., G.M. and Rohr Industries have each employed innovative tires, suspension systems, chassis/bodies and seats to create vehicles which improve the ride quality of the conventional bus by as much as 50 to 100% at speeds up to 30 MPH, and 75 to 100 percent in speeds between 30 and 60 MPH.

In addition to achieving a greatly improved ride quality, the tire/suspension system designs have allowed the floors of the Transbus design to be lowered from 34 inches as in the

current production bus designs to 17 inches, 20 inches, and 23 inches for the different Transbus designs. Longitudinal pitch, bounce, lateral stability, roll resistance, handling, stability, control and roll-over resistance have been greatly improved.

Tire Effects

The condition and behavior of the pneumatic tire primary suspension element is of paramount importance (8,9). Tire factors that can be related to ride control include the following:

1. Vertical stiffness and damping;
2. Cornering stiffness (lateral force per unit lateral displacement);
3. Slip coefficient (lateral force per unit slip angle);
4. Relaxation length and contact patch length;
5. Nonuniformity;
6. Shimmy;
7. Shake.

Other factors which affect ride quality are the conditions relating to wheel alignment. The terms camber, castor and toe-in are graphically illustrated here in Figure 15 for a typical sedan automobile. Wheel alignment is important because tire forces are quite sensitive to alignment changes (8). Toe-in is required because it puts the steering tie-rod and associated bushings into compression. This eliminates slop in the bushings which would otherwise contribute to a front-end shimmy vibration.

Factors 1 to 5 above are all properties of the tire and as such are also affected by tire pressure, type (bias ply, radial) and temperature (8). Factor 5, nonuniformity, is extremely important. As the general condition of the tire deteriorates, any nonuniformity will be exaggerated. The effect on ride quality is then particularly felt at a speed when the tire rotation frequency equals the natural wheel hop mode frequency.

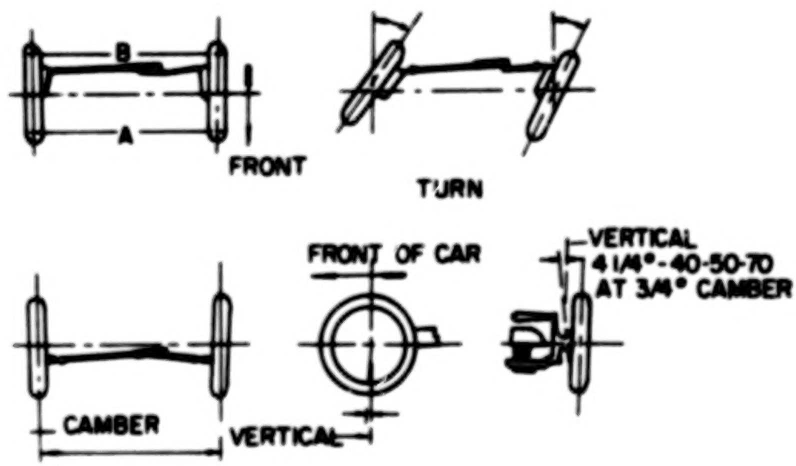


Figure 15. Wheel Alignment Variables

Increasing tire pressure, and hence its stiffness, will increase vibration levels due to tire nonuniformity.

One of the notable features of the tire is that it does have low damping and thus dissipates only a little energy in rolling. This positive fact turns to a negative fact as far as ride control is concerned, since system damping is then put entirely into the hands of the shock absorbers.

Figure 16 shows a typical measured vertical acceleration spectral density plot for a Buick Century sedan automobile over medium quality U.S. highways (10) as compared with the ISO Standard (2).

Typically, the distinction between good, medium and rough rides in an automobile is illustrated in Table 4 which relates subjective quality rating to RMS acceleration level.

Table 4. Frequency Weighted RMS g Ranges for Smooth, Medium and Rough Ride Based on Sedan Automobile Studies (11)

	S.I. Range	Frequency Weighted RMS g
Smooth ride	4.0 to 5.0	0.0 to 0.05
Medium ride	3.0 to 4.0	0.05 to 0.09
Rough ride	2.0 to 3.0	0.09 to 0.16

Automated Guideway Transit

Ride control technology in Automated Guideway Transit, using rubber-tire vehicles such as in the MORGANTOWN and AIRTRANS systems, is essentially the same as for conventional automotive vehicles, with one notable exception. The inclusion, now, of automatic steering assemblies makes the ride quality design process more difficult. Lateral accelerations are higher with vehicles that are constrained laterally (as opposed to an automobile which is free to drift laterally). Thus, steering system dynamic characteristics and the complex dynamics of rubber tires

BUICK FLOOR VIBRATIONS

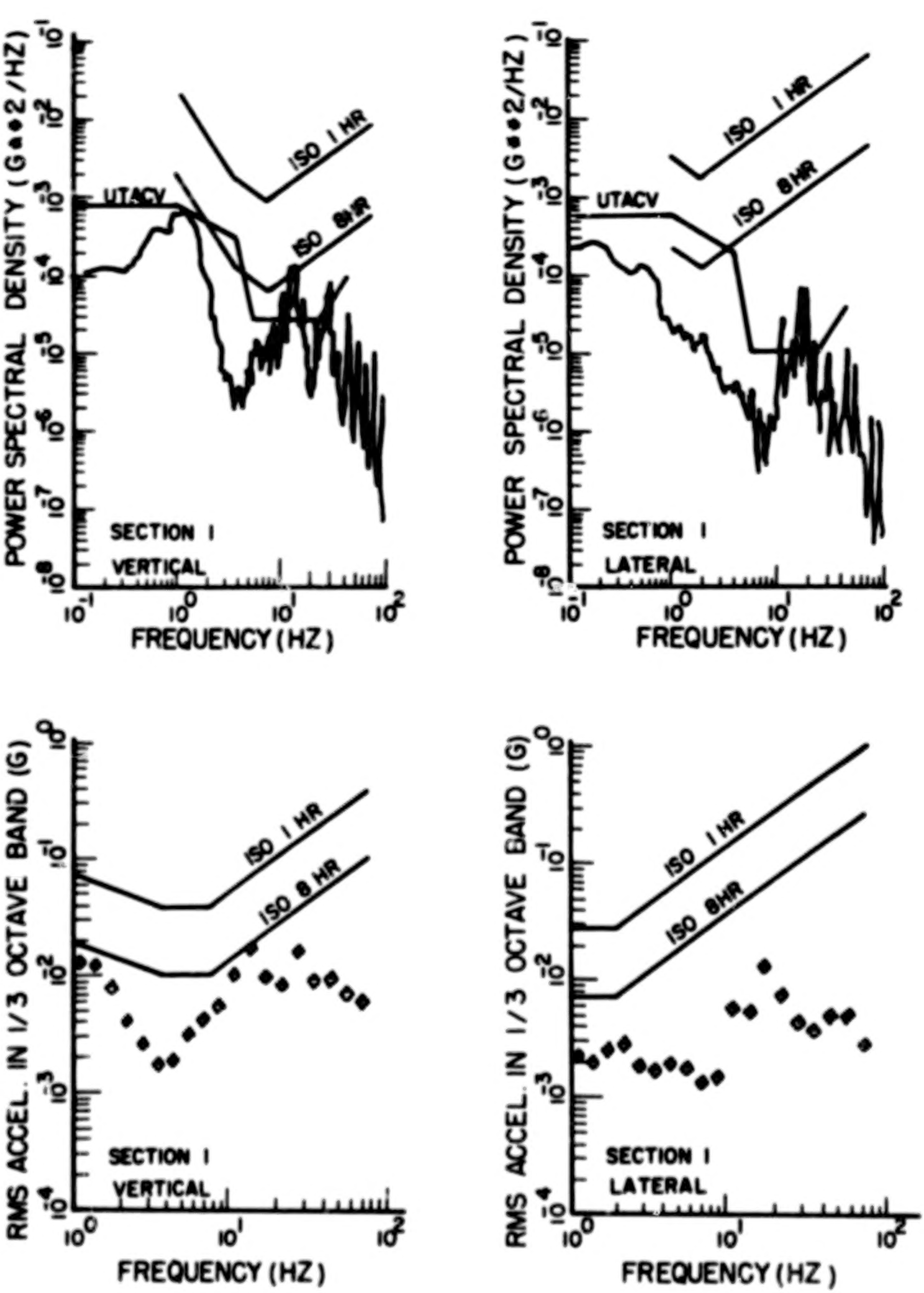


Figure 16. Typical Acceleration Spectral Density and 1/3 Octave Band Results for Sedan Automobile

must be modelled in order to arrive at satisfactory designs.

The AIRTRANS system uses a mechanical linkage for steering which is composed of a roller wheel connected by a spring to a guide bar. The roller wheel contacts the guideway sidewall and transmits guideway displacement signals mechanically to the guide bar and thence through a linkage to turn the front wheels. The AIRTRANS system is steered both front and back in order to make both wheel sets turn paths having the same curvature as the guideway. This minimizes clearance between vehicle and guidewall. A steering damper and the guide wheel spring are tuned to give the desired level of ride quality.

The vertical suspension comes from right and left rocker-beam linkages connected between the rigid axles and air-bag suspension units. The four air-bag units provide for the spring and shock damping functions and the rocker-beam linkages provide the rigid constraints between body and axles in the lateral direction. Primary suspension is through the compressions of the rubber tires, although these are relatively stiff in this system because the tires are foam-filled rather than pneumatic.

The final level of ride quality is achieved using experimental methods and empirical adjustment of spring and damping rates.

<u>Tracked Levitated Vehicle Systems</u> (TLV)

High speed (>150 MPH) ground transit requires the use of noncontacting suspensions. Candidate systems include air cushion (TACV), ram air cushion, attractive maglev, and electrodynamic maglev. Much attention has been directed towards ride quality prediction in vehicles travelling over guideways with random roughness and structural flexibility. TLV shows promise for acceptable ride quality at high speeds (240-500 km/hr), and operation over surfaces that should be economical to maintain.

Techniques for Improving Ride Quality

Simulations and limited experimental evidence have shown that TLV ride quality is determined by vehicle rigid body motions (heave, pitch, sway, yaw and roll), unsprung mass motions (suspensions, motors, power supplies), and the lower frequency flexible body modes (12,13,14). Ride quality predictions and vehicle comparisons should be based on such complete models, not on simple one-dimensional analyses. In most cases, vertical (heave and pitch) and lateral (sway and yaw) motions are decoupled and may be treated separately; vertical/lateral coupling plus roll should be considered for electrodynamic maglev, ram air cushion, and staggered lift magnet attractive maglev vehicle types.

The large contact areas in TLVs inherently improve ride quality by attenuating guideway roughness of wavelengths shorter than vehicle and pad lengths. The small gap heights needed for TACV and attractive maglev result in the requirement that the pads essentially follow the guideway profile; secondary suspensions are necessary in the 240-500 km/hr speed range to meet likely ride quality standards. Further improvements over passive secondary/primary suspension performance are possible with active secondaries (15); active primaries are not feasible due to their extremely limited available strokes (16, 17,18). Ram air cushion and electrodynamic maglev vehicles may not require secondary suspensions, but both are inherently plagued by very low damping levels. Toned suspensions (lowered natural frequencies and added frequency-dependent damping) are possible by using control surfaces and controlled magnetic loops, respectively (19,20).

Active suspensions should control the above-stated rigid body motions, and should suppress objectionable unsprung mass and flexible body modes. Krauss-Maffei currently controls heave, pitch, roll, and torsional flexure by coordinated control of the individual magnets on their attractive maglev.

Ride Control Through Guideway Roughness Control

For all ground transportation, ride quality is improved by upgrading track and overlaying pavements and in some respects, it is unfortunate to have to consider guideway control as an independent topic; that is, separate from the transport mode. However, due to the variety of modes considered in this session, there is little alternative than to proceed in this fashion. For example, marine craft and aircraft have very inexpensive but totally uncontrollable "guideways." Therefore, the vehicle response to surface waves or atmospheric turbulence must either be tolerated or modified by onboard vehicle controls. These controls may be active or passive. On the other hand, for surface transport vehicles, one can exercise any degree of control over the guideway as long as there is the ability and desire to expend the required money and resources. Thus, for ground transport vehicles, the key question to be answered is at what point does the cost of controlling the guideway "smoothness" exceed the cost of placing additional ride control systems on the vehicle. It is apparent that for ground transport systems the vehicle and guideway combined represent a system and should not be separated. Because control over guideways can be achieved only for ground transport systems, the remainder of this discussion will be so limited.

Since most at-grade guideways do not deflect significantly, the construction tolerance parameters, broadly classified as "roughness," dominate the guideway disturbance input into the vehicle. To the extent that roughness also affects elevated guideways, the following discussion is applicable to both at-grade and elevated guideways. Simulation procedures and result formats for vehicle response to guideway roughness should follow the recommendations of Hedrick, Ravera and Anderes (21). Briefly, this technique displays "equivalent ride quality performance" curves as a function of varying levels of construction tolerance

parameters. Rather than overspecifying each tolerance on a worst-case basis, this procedure will allow the contractor to choose the "lowest cost" set of construction parameters consistent with ride quality compliance. An important aspect of this technique is to define roughness parameters in terms that the <u>contractor</u> will understand, such as in the California Profilometer Index or in terms of a Maye Meter or Serviceability Index (11). Clearly, large irregularities can be individually smoothed in initial construction.

In the case of elevated guideway structures, the following design procedures are recommended:

1. The guideway should be rigid enough to be structurally sound and yet can be flexible as long as one avoids a span fundamental frequency which is too close to the vehicle primary and secondary suspension frequencies.
2. Pre-camber the guideway surface to account for dead load (weight) and live load (vehicle) deflections.
3. Avoid guideway pier spacings where the vehicle velocity V and pier spacing ℓ are such that the "forcing" frequency $f = V/\ell$ matches important vehicle response frequencies.
4. Through simulation, determine the level of required construction tolerances needed to meet ride quality. Some additional detail on this latter point (Point 4) is required and will be discussed shortly.

Some of the less obvious aspects of improving ride quality for elevated guideway structures are as follows. The dynamic response of a guideway to a moving vehicle is shown in Figure 17 where the Dynamic Amplification Factor (DAF) is the peak midspan dynamic deflection normalized by the peak static deflection of a simply supported span when the vehicle is at the span midpoint. The horizontal axis is the crossing frequency ratio V_c where V is vehicle speed, ℓ is the span length, and f is the span

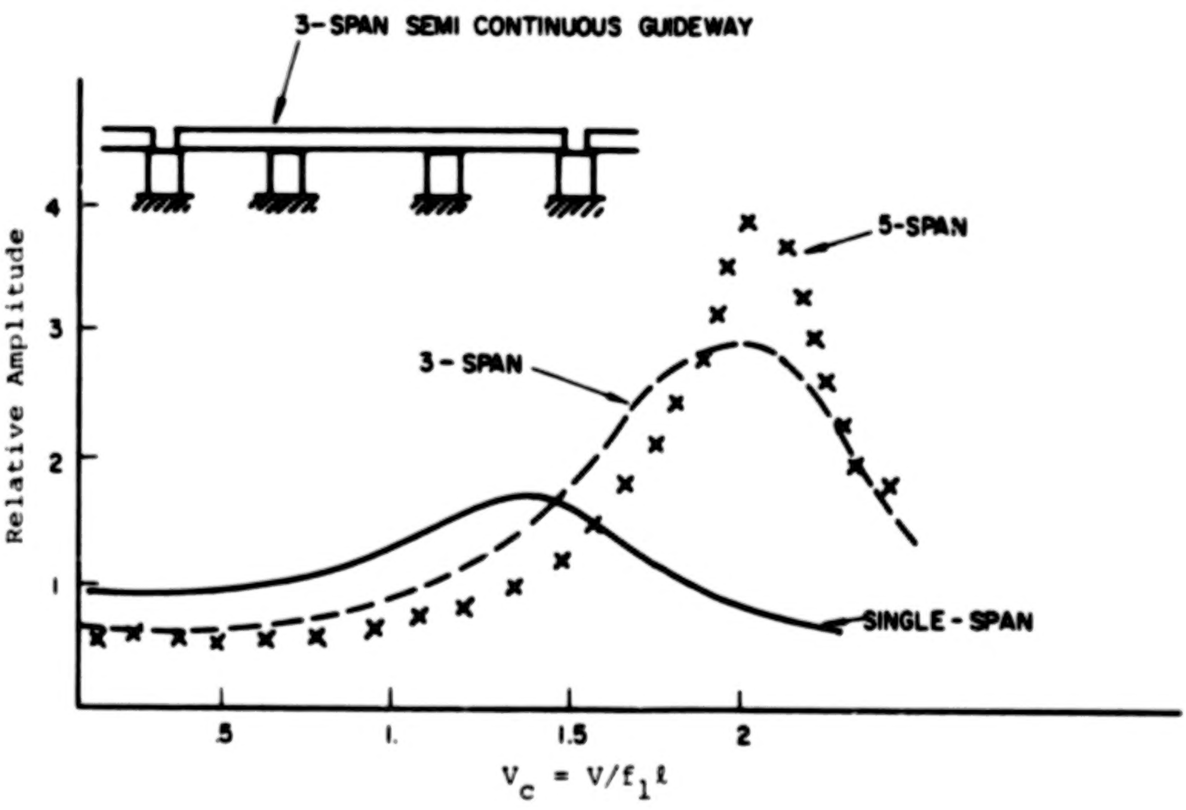


Figure 17. Dynamic Response of a Guideway to a Moving Vehicle

fundamental frequency. For a fixed guideway cross section and pier spacing, Figure 17 indicates that it is preferable to use multispan, semicontinuous guideway construction over certain speed ranges. That is, for certain speeds a lower guideway response for the equivalent guideway cross section is obtained for the multispan configuration. Multispan, semicontinuous construction means that the span is continuous over several equally-spaced intermediate supports; note that the insert in Figure 17 illustrates the three-span, semicontinuous guideway.

IMPACT OF RIDE QUALITY SPECIFICATIONS

One of the difficult problems in the conceptual design of ground transport systems is achieving acceptable ride quality while avoiding guideways which will be expensive to build and maintain. An integral part of this conceptual design is having a reliable ride quality standard. The role of the ride quality standard in answering the question of overall system cost (vehicle and guideway) is shown in Figure 18 (22). Consider that one wishes to determine the system cost differences between System A and System B where, for example, System B might be a "gold-plated" version of the System A vehicle, including, perhaps, active secondary ride controls. As shown in Figure 18, initial estimates of vehicle design and construction tolerance parameters, including flexibility, surface finish quality, etc., are used as input to a dynamic simulation of the vehicle. The vehicle response characteristics thus obtained are compared to the ride quality standard and depending on ride quality compliance, the appropriate loops are followed. If ride quality is not achieved, the designer may modify vehicle and guideway parameters separately or simultaneously until ride quality is met. When ride quality compliance is achieved, the guideway design for each vehicle is refined and then costs based on Architectural and Engineering/Contractor estimates are obtained. Finally, vehicle costs are added to the guideway costs and a total system cost can be estimated. Through this procedure, a

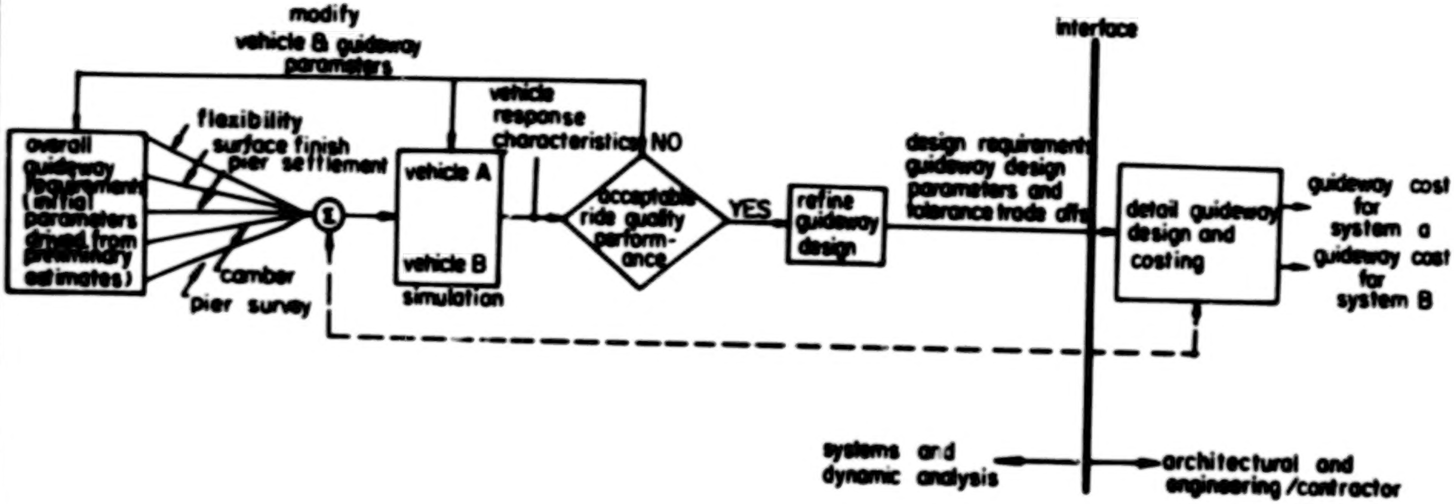


Figure 18. A Guideway Cost Estimation Procedure

cost trade-off between on-board vehicle controls and smoother guideways can be made.

The role of a ride quality standard is thus pivotal. The problem is compounded, however, because of the complex multi-directional motions that take place and the wide variety of passenger acceptance levels. Also, during a complete trip, the variability of the ride should be allowed for. The key point here is that, aside from cost considerations, systems can be made to conform to any ride quality standard imposed by the designer. How, then, should ride quality be specified?

Clearly, a ride quality standard must yield adequate passenger acceptability while, at the same time, being free enough to prevent excessive cost projections for the system. It must also be cast in a form suitable for assessing the complete ride environment expected. For example, specification of an allowable RMS acceleration frequency at 1 Hz is not enough because components at other frequencies may cause bad ride. Again, specification of an allowable level of vertical acceleration alone may not be enough when large roll acceleration with low vertical accelerations occurs.

As a final example, for rides with variable quality at different times in a trip, too restrictive specifications such as "vertical accelerations shall be less than 0.10g at all times" would impose heavy costs. Perhaps over a long trip the average ride quality should be held at 0.1g RMS with the probability of exceeding, say, 0.15g RMS held to some value such as 0.03.

Desirable Form for a Standard

A universal standard for all classes of systems does not seem possible in view of variable passenger expectations of ride in different systems. However, due to the random motion of gust loading in aircraft; the dominant tone excitation in

helicopters; the jerks due to start-stop maneuvers in automated transit, it would seem that a desirable form should combine:

1. A specification of allowed probability of exceeding a given ride discomfort index as defined, for example, using a frequency weighted RMS g evaluator;
2. A maximum discomfort index level for the trip mean ride;
3. Maximum RMS g levels for one-third octave band vibration components, taken by averaging over a trip;
4. A peak acceleration and jerk limit when filtered by a well-defined filter which passes harmful frequency components from a complex transient shock input.

From the system design point of view it would be desirable to have specifications of allowable levels of discomfort using a discomfort index, which includes provision for combined axis, rotational, multifrequency, mixed periodic, random and singular shock events. Whether or not it is possible to simply combine individual effects into a total discomfort index remains to be seen.

POSSIBILITIES FOR RIDE CONTROL IMPROVEMENT

With the thought that a rational design procedure together with advanced technical concepts may provide substantial improvement in ride quality, the possibilities and trade-off considerations were examined. This section of the report deals with some of these projections and associated trade-off considerations which are presented here by mode for convenience.

With air and sea based systems, the external environment cannot be modified; thus resort to on-board automatic control means using control surfaces for gust alleviation and ride stabilization have become state of the art. Some actual data

are available to illustrate the improvement possibilities. The same is not the case for ground transportation where control of the guiding surface is possible. Here the additional trade-off between vehicle or guideway control complicates the discussion.

Aircraft

Since active ride smoothing systems have actually been installed in a few aircraft, this section deals with the results and trade-off considerations.

Results

The following are results of experimental and analytical studies on ride smoothing.

A. Landing Gear Design (23)

By the implementation of a dual chamber design landing gear the landing impact was reduced from a .4g peak to a .2g peak. Also, the taxi cockpit RMS acceleration was reduced from .2g to .11g.

B. Rigid Body Motions

From flight data (24), improvements in a Jetstar may be summarized as follows:

	RMS Acceleration		
	Vertical	Lateral	Passenger Acceptance*
Basic Aircraft	.11g	.05g	65%
With Ride Smoothing	.05g	.02g	94%

A theoretical study (5), on a projected STOL application indicated the following improvement:

	RMS Acceleration		
	Vertical	Lateral	Passenger Acceptance*
Basic Aircraft	.12g	.03g	59%
With Ride Smoothing	.04g	.03g	86%

*Established by U.Va. acceptance model (27).

C. Flexible Aircraft

B52 Controls Configured Vehicle (CCV) yielded 30% to 50% reduction in rms acceleration at either end of fuselage for isolated-area reduction (1). From analytical studies it is estimated that a minimum of a 30% reduction in whole-body RMS acceleration levels can be achieved using flap, elevator, and canard controls.

Trade-Offs

The trade-offs to be considered for the introduction of any new aircraft may be very extensive and in-depth depending upon the system development phase; therefore, it is assumed that first-level trade-offs are only considered here.

The primary trade factors to be considered are:

1. Safety;
2. Performance;
3. Cost--initial and return of investment;
4. Reliability/maintenance costs; and
5. Weight.

It is usual that the introduction of new function capability tends to (and in most cases does) result in significant improvements in other areas, e.g., ride quality improves fatigue life significantly; the potential side benefits must be sought out. Other possible benefits should accrue from reduced maintenance costs. The techniques described above are all state-of-the-art with low development risk; therefore, the substantial cost elements could be well defined. The introduction of active devices that could affect aircraft safety needs careful study over all plausible operating situations to ensure maintenance of a high level of safety. Possible benefits may well outweigh slight degradation.

Anticipated Problems

1. The establishment of necessary data and verifying their sufficiency to implement trade-off studies and to

establish required relationships between ridership and physical motion parameters is a major concern.

2. Customer acceptance of aircraft rides having various degrees of ride roughness needs extended verification. Do the University of Virginia models of acceptance and comfort apply universally and can this be verified? Do such models apply to large flexible aircraft as well as to smaller rigid aircraft?
3. Does a true need exist for ride smoothing systems on STOL aircraft? Will there in fact be any real change in passenger use when ride smoothing systems are installed?
4. Performance decrements due to the operation of ride smoothing systems will occur. What trade-offs exist between these decrements and ridership gains?
5. Handling quality degradation in turbulence needs quantification.
6. Reductions in handling qualities and pilot available control authority when ride smoothing systems are operating are possible.
7. Reliability problems will exist with ride smoothing systems. Such systems may not be a safety of flight item and may not require as rigid regulations as basic flight systems.
8. Ride smoothing systems will increase maintenance requirements. On large aircraft the systems may not be any more complex than other existing systems thus not requiring special expertise. On small aircraft, this may not be true.
9. Airline maintenance personnel acceptance of and training for ride smoothing systems can cause difficulties.
10. Obtaining necessary funds to conduct studies and verify concepts may be a major problem.

Needs for Future Work

Airborne

First of all, it appears that a great need is in the quantification of passenger reaction to some ride quality variable that can be easily instrumented and measured. The University of Virginia has come a long way in obtaining equations based on motions of commuter aircraft (10 to 25 passengers). Two questions are immediately apparent.

1. How does the University of Virginia work apply to larger, more flexible aircraft where motion is composed of low frequencies from maneuver modes and high frequencies from structural modes?
2. How can this baseline work be used to determine the influence of a ride smoothing system on passenger acceptance, thus reflecting ride quality system cost into the ROI of a certain aircraft?

It would appear that the answer to the first question might be found by verification through flight test. This might take the form of a measurement and questionnaire study for representative aircraft types similar to the short-haul work already done. Alternatively, a test aircraft such as the NASA 737 could be instrumented and data taken with subjects during the course of its operation for other programs.

The answer to the second question may be had in one of two ways. Perhaps a reduced level of acceleration could be picked which would be representative of that obtained with a ride control system and a resulting improvement of ridership could be determined. Then the cost of a ride control system could be estimated based on experience which could be reflected into initial cost and rate of investment. Perhaps another way to do this would be to implement a ride control system on an aircraft similar to the University of

Virginia baseline aircraft and put it into service for comparison. Some work has been done on a study to accomplish this on a DHC6 Twin Otter. Similar programs have been conducted for other modes of transportation such as with the Light Rail Transit Vehicle, the State-of-the-Art Car, and the Transbus. These programs involved building new vehicles while ride control system implementation requires only modification of existing equipment.

A third area that should be investigated is the effect of a ride control system on flying qualities. Evidence exists that turbulence degrades flying qualities and the positive effects on safety smoothing through use of a ride control system should be assessed for various levels of turbulence. Also related to this area of concern is the need to establish and verify stability and control effects on boundaries with regard to enhancing ride quality.

<u>Ground</u>

There also exists a need for improved ride during the taxi/takeoff/landing phases of aircraft operation. This need arises from the unfavorable response of aircraft to taxi/runway inputs. There has been work accomplished in the area of providing improved passive landing gear systems that has significantly improved the situation but not completely solved the problems. There is, then, a need to conduct analysis/trade-off studies between passive and active landing gear systems. Present passive systems should be optimized to allow the most significant tradeoffs with active systems.

Benefits of improved systems would include increased passenger acceptance and decreased pilot workload with accompanying increase in safety.

Finally, work being accomplished in the advanced specification of pavement criteria and capabilities for meeting these criteria

being considered for surface transportation modes should be applied to runway surfaces to reduce adverse surface inputs.

Sea-Based Systems

With boats, the improvement of using a fully-submerged hydrofoil with active control was illustrated in the previous section and in Figure 9. Apparently the additional complexity can achieve a reduction from 0.1g RMS to 0.04g RMS for the same sea state. Since the fully-active system is state-of-the-art in the marine area, the remainder of this section will deal with the improvement from a trip point of view and consideration of problem area.

Table 5 applies to recently established operations in Hawaii (the first commercial inter-island boat system in 25 years). Service started in June 1975 so data are scant. The only valid comment at this stage is that while the airplane is almost the same price, the trip time can be misleading since the drive to the airport is both time-consuming and exasperating. People are preferring the one mode in pleasant surroundings. We will see how the market goes.

Table 6 provides an opportunity to compare choices. The traveling public are tourists and Chinese gamblers between Hong Kong and the island of Macao. The traveler can go by conventional steamer, pay \$3.08 and get there in over 2 hours; or he can go by one of the available 20 surface-piercing hydrofoils, pay \$4.10 and get there in 70 minutes. Finally, he can pay \$6.15, go by fully-submerged hydrofoil (JETFOIL) and get there in 50 minutes. There are seven trips per day.

Apparently, the traveler is willing to pay approximately 50 percent more to get to the gambling tables 20 minutes earlier.* The traffic figures are a little difficult to come by, but approximately 3 million or so people travel this route per ye The current traveling rate of passengers by fully-submerged

*Perhaps he hopes to win the difference back.

Table 5. JETFOIL Operations in Hawaii

Trip	Distance (n.m.)	JETFOIL Trip Time	JETFOIL Seat Ticket Price	Airplane Trip Time	Airplane Seat Ticket Price
1. Oahu to Kauai	98	2 hrs. & 30 mins.	$20	25 mins.*	$23
2. Oahu to Maui	85	2 hrs. & 10 mins.	$20	25 mins.*	$23
3. Maui to Hawaii	76	2 hrs.	$20	25 mins.*	$23

*Does not include driving time to airport (of approximately one hour).

Table 6. JETFOIL Operations in Hong Kong

	JETFOIL	Partially Submerged Foil	Steamer
Trip Distance	36 n.m.	36 n.m.	36 n.m.
Trip Time	50 mins.	70 mins.	2 hrs. & 20 mins.
Speed	43 knots	30 knots	15 knots
Wave Height	3-5 ft. max. 2-3 ft. normal	----------------	---------------→
Ride Quality	Excellent	Marginal	Bad
Seat Price*(U.S. $)	$6.15	$4.10	$3.08
Craft Cost	$7M	$1.5M-2M	?

*Prices quoted apply to weekdays (20% increase for weekends). Also quoted in U.S. $ at exchange rate of $1 (U.S.) = $4.88 (H.K.).

hydrofoil is 1000 passengers per day per craft. Is it the better ride, the shorter trip time, or the novelty that is accomplishing this? Some recent passenger reactions to the ride are as follows:

1. No reported cases of travel sickness;
2. The speed of 43-48 knots is described as pleasurable because the travelers enjoy overtaking the other boats;
3. The trip time is short;
4. A definite improvement in ride quality (0.02-0.03 g's RMS typical);
5. The wide body spaciousness feeling compared to the tubular closed-in feeling of the competing boats;
6. The noise level is lower and comparable to the interior of a jet aircraft;
7. Seasickness is reduced considerably by the psychological effect of large windows giving the traveler the "connection" to the outside world;
8. The improved capability of being able to eat and drink while underway without excessive motion.

Hence, while motion is a dominant factor, it is the combination of the motion (or lack of it) and the items in the above list that constitute good ride quality. What we have to do now is get the price down!

As a comparable number for air cushion craft, the 190-ton SR.N4 will cost approximately $7 million in 1975 dollars and travel at 50 knots in similar sea conditions from England to France for a trip time of approximately 50 minutes.

Anticipated Problems

These can be stated simply as:

1. Reduce the basic cost of both fully-submerged hydrofoils and air cushion craft or there will be insufficient operators prepared to make the initial gamble of

introducing a new service despite the projected long-term operating cost advantage. A goal of 50 percent of current craft costs appears reasonable. This may require a reduction in ride quality or sea state capability. New thoughts are required here.

2. The state-of-the-art of ride control of hydrofoils is well established. This cannot be said of air cushion craft. The problem still remains of developing an active ride control system that does not waste large amounts of power.
3. Development of an acceptable set of ride quality criteria based on reliable data gathered "in the field" on each of the various forms of marine vehicles.

Ground-Based Systems

Based on data so far, it appears that the largest improvement in ride quality will come from guideway and track maintenance, upgrading and improvement, with the possibility of up to 10:1 improvement. Figure 14 illustrates for the Metroliner that approximately 30% reduction in the low-frequency RMS content (0 - 5 Hz) may be achieved by fine-tuning of the passive suspension spring and damping rates. Thus, by improved maintenance, at least 30% reduction could be found if the additional expenditures were made. Figure 19 shows that considerable improvement in noise levels can be achieved by liberal use of rubber bushings and air rather than metal spring elements.

From the same Metroliner prototype truck development program, an estimate of the cost of improved passive suspension design is available. The proposed price for a truck, based on the prototype design and intended for the new Amtrak bi-level cars, was $2,000 (about 6%) over the price of the low bidder. Since the Amtrak specification required only that the new bi-level cars have a ride equal to that of the old bi-level cars, the builder had no choice but to select the low bidder.

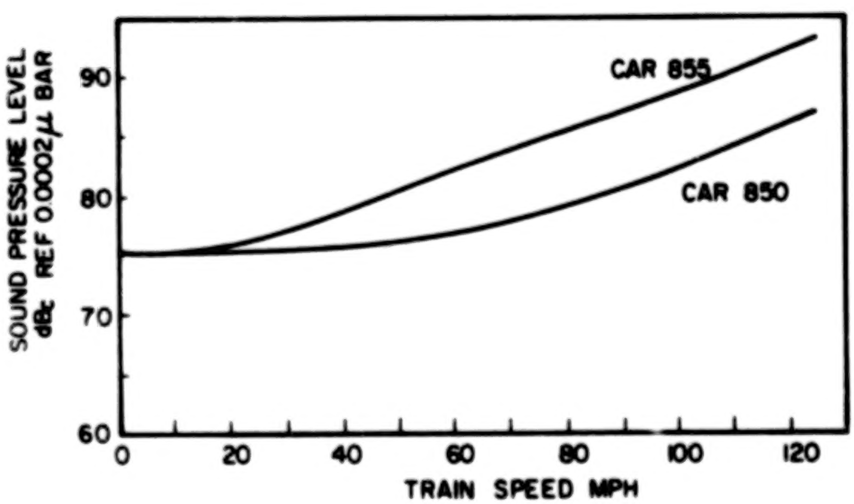


Figure 19. Comparative Noise Level Measurements for the Two Running Test Cars

The following areas need further research in passive rail system design:

1. A consistent measure of ride quality which can be obtained by measurement reduction in real time;
2. Application of ride quality standards, stated in terms of this measure, which properly represent the state-of-the-art;
3. A continuing documentation of reliability of suspension components, with feedback to the manufacturers;
4. A long-term examination of the way in which wheel profiles wear, including the effects of suspension characteristics, track condition, and shape of initial profile.

Active Suspension Systems

Active suspension systems can logically be considered only when the designer is confronted with an objective which cannot be handled with a passive suspension system. In rail system design there are two obvious possibilities:

1. Active roll control to permit higher speed in curves;
2. An active actuator to smooth lateral transients.

Although roll control is coming into use in Europe, its application in the U.S. will be far more limited. This is true for the simple reason that U.S. track has fewer curves which significantly limit speed. In view of the present state of U.S. track, an active lateral actuator is appealing, but could only be justified as an alternative to upgrading the track. In view of the present difficulties in maintenance of conventional equipment, its application seems impractical.

For automotive vehicles, significant ride quality improvements are not likely to be achieved. The strongest factors influencing ride are the roadway or terrain roughness and the vehicle speed Roughness effects are illustrated in Figure 20

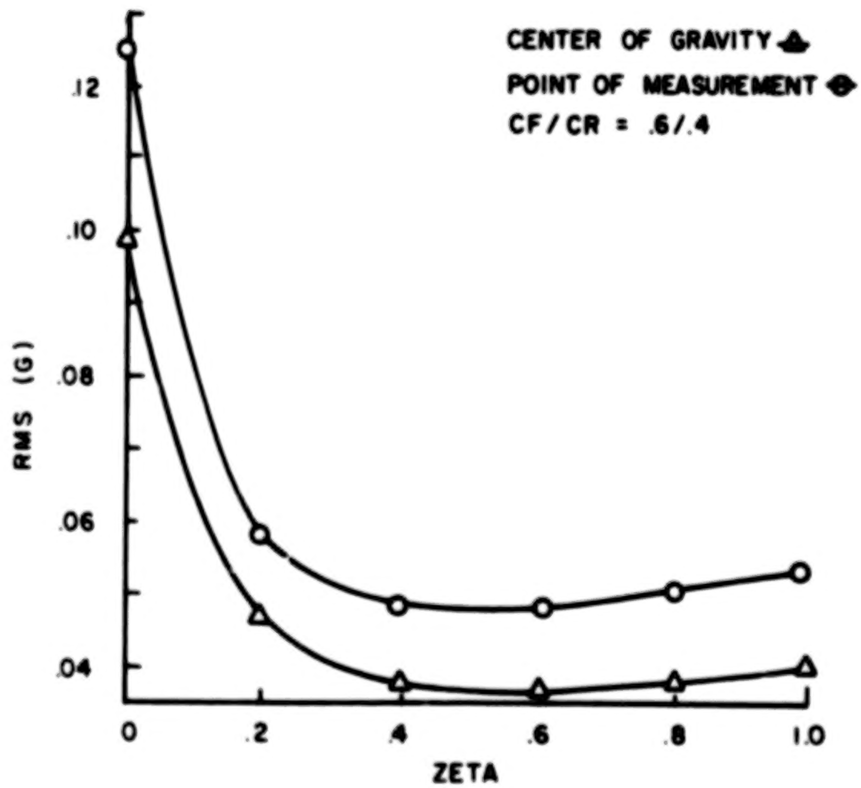


Figure 20. Vertical RMS g Acceleration Versus Roughness in RMS Inches (25)

for a Buick Century sedan automobile traveling at 50 mph over various roadways.

With low RMS roughness, say less than 0.4 inches, roughness has a strong influence. Larger roughness effects cannot be easily identified, however, because different wavelength inputs have varying effects according to the vehicle transfer function characteristic which isolates large roughnesses even using conventional passive isolation systems.

Speed effects can be estimated to cause at least a 1/2 power increase in RMS acceleration. Roughness inputs increase with the 1/2 power of speed whereas other excitation sources from unbalance and wheel nonuniformity have larger effects at their critical speeds.

For the same speed and the same road, only small improvement is likely. Figure 20 illustrates the effect of shock damping rate on automobile acceleration response as predicted for constant speed and the same road (25).

A possible 30% variation in RMS acceleration as a function of shock condition seems likely.

The primary tradeoff consideration in motor vehicle designs is between softening the suspension at the expense of increased roll and sway in the curves. This is more critical with heavy trucks. With trucks, the considerations lean toward stiffer suspensions at the expense of ride. Figure 21 illustrates the nearly four to one increase in discomfort based on frequency weighted RMS g acceleration in heavy trucks over automobiles for the same road and speed (26).

The additional tradeoff using active roll banking and active suspension elements for cab and body isolation are at the expense of significant increases in complexity and the attendant problems with reliability. Unfortunately, very limited information exists

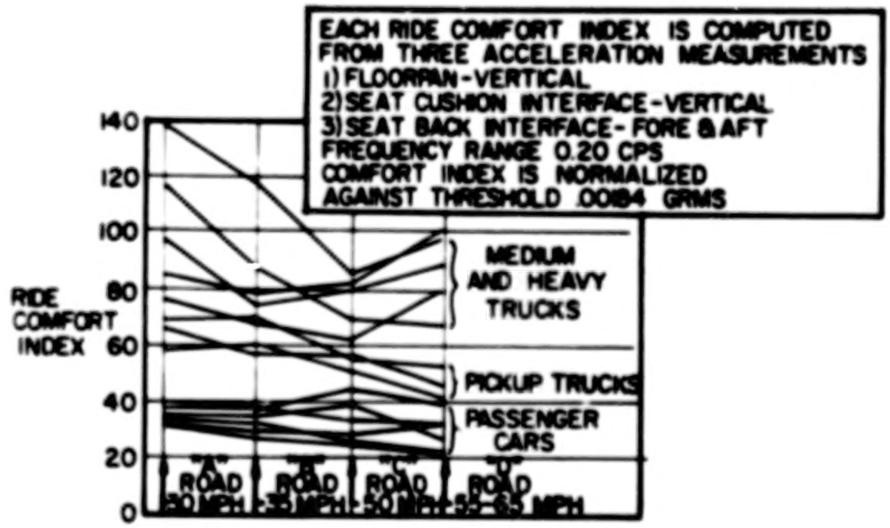


Figure 21. Ride Comfort Based on Frequency Weighted RMS g Measure (26) Versus Speed

on the improvement capabilities of active ride control systems in motor vehicles.

Based on guesswork at this time, it seems that ride quality of the auto can be improved somewhat by active control. Possibly a 30% reduction in RMS g vertical acceleration could be accomplished by this means. Active or semiactive control would require accelerometers for heave and pitch with a servo actuator to provide additional suspension force in parallel to that of the passive secondary.

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APPENDIX I

ON SCALING TECHNIQUES

This section is intended as an introductory review of the principles of scaling with emphasis on ride quality work. It will be divided into six parts as follows: (1) Definition of Scaling; (2) Scope and Goals of Scaling; (3) Scaling Techniques (with emphasis on rating scale, magnitude estimation procedures and cross-modality matching); (4) Laboratory vs. Field Studies; (5) Multivariate Analysis; and (6) Selected References.

1. Definition of Scaling

Scaling as applied to ride quality generally refers to assigning numbers to degrees of discomfort, annoyance, etc., so that the relations between the amounts of a sensation can be represented by real numbers. It is then possible to associate these numbers with numerical measures of the physical quantities considered important and controllable in the design of equipment, operating procedures, and other system variables.

Several types of scales are available. An ordinal scale allows one to know only the ordering of objects--there is no meaningful interpretation of the differences between the numbers.

With an interval scale, numbers again reflect the order of the objects with respect to their properties, but also the magnitudes of the differences between numbers quantitatively represent differences in the property. Thus, an interval scale has a unit of measurement.

Using ratio scales, one can determine the equality of ratios of the property of interest and therefore speak meaningfully of equal ratios of numbers. A ratio scale has

not only a unit of measurement, but also a zero point, i.e., an origin.

In each of the above cases, the problem is how to represent an empirical system (a set of objects and the relations that hold between them) with a numerical system (a set of numbers and the relations that hold between them). In selecting one of the three scale types, the issue is simply to select the best numbering system to meaningfully represent the properties of the empirical system, so that the maximum amount of information can be extracted.

It is important to choose the type of scale carefully, since in order to utilize the more powerful tools of statistical analysis (parametric statistics), the data must be available in interval or ratio scales. On the other hand, the simpler and less powerful types of analysis (nonparametric statistics) are generally considered appropriate for data which have only ordinal or nominal characteristics and/or are not normally distributed.

A further distinction can be made between scaling formats. A unipolar scale has only one direction of magnitude. Thus, if a sound is presented to an individual who is requested to rate the loudness of that sound, then the scale needs to go only in one direction. Intensity and the human's perception of it start at some zero point and can only increase from that point, and decrease to it. A bipolar scale is used when the dimension, attribute, or property of interest can vary in two directions from a zero or neutral point. Considering such a dimension to be good-bad, it must be assumed that a neutral point exists (neither good nor bad), and that the various experiences which can be encountered can fall on either side of this neutral point.

2. Scope and Goals of Scaling

In relation to ride quality work, the purpose of scaling subjective responses is to achieve a better understanding of

the influence of vibration and noise on humans, and to develop "limits" for these properties as well as "criteria" which can provide an indication of the extent of human reaction to them. These criteria are generally involved with a comfort-discomfort dimension. Such a dimension is in itself complex, having three major components: (1) subjective comfort-discomfort; (2) activity disturbance; and (3) physical discomfort. The first component is by far the most difficult to deal with, and it is also the one which is most significant in ride quality evaluation.

The word <u>criteria</u> causes some problems since it does not have a universal connotation among engineers and behavioral scientists. To an engineer a criterion is generally taken to be a limit or boundary not to be exceeded, or a standard to be met. For psychologists the criterion is the dependent variable, the value to be predicted using other known (or independent) variables. Engineers seek criteria in the sense of design limitations or specifications to be adhered to. Thus, criteria for ride quality would be a set of stated limits which the vehicle must not exceed if ride quality is to be acceptable. Comfort will be an important variable in determining what these limits are. The limits will be stated as levels on the motion, noise, temperature, or other physical variables.

In discussing the scope of scaling, one must be concerned with the question of what to scale, i.e., what the subjects should be asked to judge. Clearly, the ride environment is multifactored; that is, the person in the environment is influenced by (acted upon by) motion, vibration, noise, temperature, etc. The issue is whether some global reaction to the environment and its effect should be assessed, or whether subjects should be asked to respond to each of the aspects separately. The choice must be made in accordance with the goals of the particular research effort. The point being made

here is that "what makes people comfortable or uncomfortable?" is a different question from "how do people react to vibration?".

Since comfort refers to a subjective reaction, it is appropriate to look toward well-structured theories of comfort to guide research and to help design the proper measurement techniques. The psychological literature on construct validity is a place to start. For example, Dulany's theory of verbal conditioning[5] is a self-conscious attempt to develop a theory involving subjective states of the person. Research about subjective states of a person requires a commitment to theory and a concern for multiple hypotheses about the state of interest. Rating scales, and indeed judgment methods in general, represent but one way of having people relate how they feel.

3. Scaling Techniques

The sensations of interest to ride quality research involve the level of discomfort, annoyance, satisfaction, pleasure, etc., that passengers experience during a ride. The way the effects of the ride are assessed is by asking people to tell how they feel as a result of experiencing the ride. There are three basic ways of doing this: rating scales, magnitude estimation, and cross-modality matching.

With a rating scale, the subject is asked to place the stimulus object in a category or to assign a number to it reflecting the amount of a property he or she believes it displays.

In a standard magnitude estimation task, the subject is given an object and told that a fixed number (say 10) represents the magnitude of the property in that object. Then a second object is presented and the subject must assign a number to it to express how much of the property this new object has. Thus, the subject is given a standard and required to directly estimate

the magnitude of the property associated with other objects. The number assigned to the standard defines the modulus or unit of measurement for the judgments of the subject.

Cross-modality matching avoids eliciting numerical estimates from subjects. A stimulus is presented in one modality (e.g., loudness of a tone), and the subject is then required to adjust a stimulus in a second modality (e.g., the intensity of a light) to match the sensation produced by the first stimulus.

These alternative methods are discussed in the following sections.

a. Rating Scales

With a rating scale, a person is asked to indicate the strength of his or her sensation (e.g., annoyance) that occurs as the result of a physical stimulus (e.g., noise). The variety of different subjective rating scales that have been used by researchers is enormous. These scales can be characterized as varying according to (1) Scale Format--for example, whether the scale consists of boxes and is discrete in nature, or is of a line variety and continuous in nature; (2) Number of Scalar Points--the number of demarcations on the scale; (3) Polarity--unipolar or bipolar; (4) Physical Length of Scale; and (5) Adjectives and Adverbs Used as Scale Anchors--either attached to the scale itself or to demarcation points along the scale.

In particular, using a rating scale in comfort studies raises some interesting points. First of all, there seems to be no firm agreement among investigators as to whether a comfort scale is unipolar or bipolar. Some feel that people view comfort as a neutral, baseline state; hence, any effect of motion can only make them uncomfortable--a unipolar situation. Others claim that the comfortable-uncomfortable contrast is a perfectly normal bipolar reaction, and that the controlled stimuli can easily be changed to produce an effect in either direction. It is not clear

that this issue is of much significance, except perhaps in the matter of standardization.

There does seem to be general agreement on the fact that a reasonably large number of points on a scale (say 7 to 11) is beneficial for producing useful information. Scales with small numbers of points should be avoided since subjects tend not to use the end points. Hence the number of useful points is ($\underline{n}$-2), where $\underline{n}$ = the total number of scale markers. One technique known as <u>certainty scaling</u> uses a ten-point scale. The respondent first makes a decision as to being comfortable or uncomfortable. This locates the response on one half of the scale or the other, with five points on either side for reflecting the intensity of feeling. Thus, a binary decision is followed by a five-point rating, yielding a total of ten levels of the attribute of concern.

The rating line method is often used in comfort research. The main advantages are to give the subject an opportunity to express his or her impressions freely, and to give the investigator the chance to select his scale after the information has been registered. In the end, however, all the marks on a continuous scale must be coded as numerical data of either integer or decimal values. The length of the scale seems to have no significant importance, either in a practical or theoretical sense.

Descriptive labels for rating scales are of considerable importance. In ride quality research the object is to determine the subjective correlate of the quality of the ride. The question which must be determined is--what internal state best reflects variation in assessment of the ride? Comfort, pleasure, or satisfaction seem to be natural indicators of this state. Other adjectives may be more appropriate for particular stimuli, e.g., annoyance judgments for noise; smoothness judgments for certain motions, etc. Comfort is a general dimension, and variation in it can depend upon any or all of the multiple factors in the physical environment.

With regard to anchor points, one must be careful about adding adverbs to modify adjectives. If the endpoints of a rating line are labeled "very comfortable" and "very uncomfortable," fewer respondents will mark close to the ends of the scale than if the labels are just "comfortable" and "uncomfortable." A research study by Cliff[2] has established that adverbs may indeed function as multipliers in evoking a rating from a judge. The following guidelines are appropriate for the use of labels:

(1) The use of labels such as comfort-discomfort seem to be the most appropriate for ride quality research;

(2) The labels should be carefully chosen to be appropriate to the goals of a project;

(3) The scale labels should be defined and clarified in the instructions to the subject;

(4) The scale labels should remain consistent across the scale; e.g., if one end of a vibration scale is anchored with the word "pleasant," then the other end should use "unpleasant"--not "uncomfortable."

b. Magnitude Estimation

As defined earlier, this method involves a ratio type of scale in which the judge is asked to compare the magnitude of a stimulus with that of a standard. The basic advantages and disadvantages of this method are summarized in the report of Group IIIB, although it should be stated that there is by no means an unanimity of opinion concerning them. In addition, there is a problem with magnitude estimation in a field study, as it is often difficult to properly present the necessary standard stimulus. Finally, there is some question of how readily a general group of subjects will be able to do the required task. As most lab instructors in experimental

psychology will attest, college students need considerable training in order to perform adequately on magnitude estimation tasks.

c. Cross-Modality Matching

This is probably the most complex technique of all and, although suitable for laboratory studies with specially-trained subjects, has not yet seen much application in the field or with a general subject population.

4. Laboratory vs. Field Studies

It is not possible to tacitly assume the comparability of results obtained in each of these situations. Important differences may arise as a result of the realism of the situation, the nature of the respondents used, and the demands placed on the respondent.

In performing field studies, the subject group is the general traveling public. They usually respond to questions out of courtesy and interest, but care must be taken not to ask too much of them. If the questions are too complex or the surveys too long, they may refuse to participate or lose interest, and the validity or quality of their responses becomes suspect.

Laboratory subjects are often a highly selected subset of the general population. They are a captive audience and are usually paid for their services, or are getting time off from other duties. They are usually highly motivated and eager to respond to the tasks or questions placed before them. There is, however, the risk that their responses and reactions may not be representative of the population of interest. Therefore, great care must be exercised in the selection of laboratory subjects. An investigator should always report possible subject attributes which could influence the pattern of outcomes, including (a) whether subjects volunteer or are solicited; (b) whether or not subjects are paid; (c) the extent to which subjects are trained or have previous

experience in the experimental task; and (d) what factors might influence the level of motivation of the subjects.

Laboratory subjects are often required to respond to a wide range of situations, whereas a passenger on a public service vehicle is usually asked for limited responses. Do the experiences of laboratory subjects alter their reactions over time? Laboratory subjects can be instructed in how to respond to questions (i.e., the general types of answers required), but it is difficult to achieve this level of comprehension with impromptu interrogation of passengers. In an experiment, techniques can be carefully explained to insure their validity and reliability. In the field, the questions must be self-explanatory and easily answered. Category rating scales appear to be readily understood by most people, but magnitude estimation techniques are less comprehensible.

Laboratory simulations may vary in their fidelity and degree of realism. The investigator must assess the degree to which any lack of realism might influence the results and their implications. As evidenced by the review papers presented at the Symposium on Ride Quality(17), there is support for use of both ground-based and in-flight simulators for research in ride quality in air transportation. Where comparisons have been made, the validity of the simulators seems to be good. But what is most important is that comparisons have been made. Laboratory results are often representative of the field situation. But the correspondence of the laboratory and the real world must be periodically assessed. It is up to the experimenter to consider the representativeness of the sample, the rationality of the methods, and the validity and generalizability of the results and their implications.

5. Multivariate Analysis

The issues involved in using a single rating scale to reflect variations from several factors, or types of input, merits further discussion. Techniques for assessing the effects of each of

several inputs on the dependent or response measure include: (a) multiple regression; (b) analysis of variance; and (c) multidimensional scaling.

a. Multiple Regression Analysis

This is a statistical procedure for relating a linear combination of several predictor variables to a dependent or criterion variable. It allows the determination of the relative importance of each of the several predictors to the criterion. Standard computer programs obtain a set of weights for the linear combination, which maximizes the correlation of the independent variable levels with the criterion scores. Standard references on this technique include Ezekiel and Fox[6], Draper and Smith[4], and Darlington[3]. The SPSS library of computer programs includes a good multiple regression program[11].

b. Analysis of Variance

Analysis of variance is a special case of the same General Linear Model as multiple regression. In an analysis of variance, the experimenter selects particular factors of interest and selects levels of these factors to be included in the experimental design. Analysis of variance is useful because it allows an investigator to assess the influence of each factor (independent variable) alone, as well as the effects of various combinations of levels of the several factors (interactions). Analysis of variance is particularly useful for the detection of such interaction effects. If there are no interactions between factors, then an additive model involving the independent variables is adequate to explain variations in the criterion measure. If there are interactions worth including in the model, the model is said to be configural.

The most extensive research program using analysis of variance models is that described by Anderson[1]. His studies on information integration theory are a classic exercise in isolating

the determinants of judgment and perception in laboratory experiments. Anderson uses rating scales (similar to those discussed previously) and factorial designs coupled with analysis of variance to study how people integrate the information provided them to arrive at a judgment, or rating.

Another related research development is additive conjoint measurement. This technique involves rescaling variables (both dependent and independent) in order to attain additivity of the main factors, i.e., to eliminate interactions. Various conjoint measurement schemes are presented by Shephard[13].

c. Multidimensional Scaling

Multidimensional scaling has been developed to extract the spatial dimensions necessary to explain variation in similarity or preference data. The rating given in most tasks is the degree to which two stimulus objects are similar or dissimilar. Judgments of the pairwise similarity of all stimulus objects are entered into one of the standard scaling programs. The computer then extracts the best dimensional model for the data, given a particular number of dimensions. Scaling procedures may be applied directly to similarity ratings given by judges, or they can be applied to similarity coefficients computed from sets of ratings on other scales. An introduction to multidimensional scaling is given by Green and Carmone[7].

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APPENDIX II

LIST OF PARTICIPANTS (WORKSHOP GROUPS)

Group 1 - Accomplishments in Ride Quality Research--Present and Near Future

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Special Participants

The following individuals will participate in the workshop in the special capacities indicated.

Adrian Clary, National Research Council/Transportation Research Board

A new Ride Quality Task Force has been formed in TRB under a section for which Mr. Clary serves as Secretary. Mr. Clary will float among the four groups as an observer.

A.R. Kuhlthau, University of Virginia

Mr. Kuhlthau will circulate among all four groups with the responsibility for providing coordination of activities of the groups on a real time basis as the need becomes apparent.

Terrence Rezek, NASA/Flight Research Center

Mr. Rezek will float among all four groups as an observer for the Flight Research Center.

Raymond P. Whitten, NASA/Headquarters

Mr. Whitten will divide his time between Groups 1 and 2.

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